Multiple-Part-Type Production Scheduling for High Volume Manufacturing (Time-Based Approach)

by

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Submitted to the Department of Mechanical Engineering on August 19, 2008 in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Manufacturing

Abstract

An effective production scheduling strategy would lead to efficient production line performance as well as increased profit. However, there is no fixed or generalized solution. In this thesis, Nonlinear Programming and time-based Control Point Policy were applied in sequence to solve the production scheduling problems at a high volume industry. The strategy provided the company a systematic way to tackle production problems. A distinct tradeoff between average inventory and frequency of changeover is observed. A recommended selection is made based on minimizing total cost (inventory holding cost and changeover cost). Comparing with current line behavior, the recommended selection will reduce the total cost by more than half.

Key words: time-based Control Point Policy, nonlinear programming, production scheduling, changeover, inventory

Disclaimer: The content of the thesis is modified to protect the real identity of the attachment company. Company name and confidential information are omitted.

Thesis Supervisor: Stanley Gershwin
Title: Senior Research Scientist of Mechanical Engineering

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Finally, I'd like to thank my wife, Lingying Liu, for all the love and support she has given to me.

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List of Notation

H	=	Hedging Time
U	=	Upper Hedging Time
L	=	Lower Hedging Time
U_i	=	Upper Hedging Time for part type i
L_i	=	Lower Hedging Time for part type i
TC	=	Total Cost
IC	=	Inventory holding Cost
MC	=	Extra Cost to produce on the manual line
E	=	Extra Cost due to produce one unit on the manual line
P_{tmA1}	=	Production on auto-line 1 of part type m in time period t
P_{tmA2}	=	Production on auto-line 2 of part type m in time period t
M_t	=	Manual-line production in time period t
D_{tm}	=	Demand for part type m in time period t
CP_{tm}	=	Cumulative Production on auto-lines for part type m in time period t
CM_t	=	Cumulative Production on the manual line in time period t
CD_{tm}	=	Cumulative Demand for part type m in time period t
I_w	=	Cost of holding unit inventory for one week
I_M	=	Cost of holding unit inventory for one month
C_{AL1}	=	Capacity of the auto line 1 per week
C_{AL2}	=	Capacity of the auto line 2 per week
C_{Mt}	=	Capacity of the manual line per time period

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Chapter 1 Introduction

In this chapter, we will provide a brief introduction of Ailter Electronics Singapore Pte Ltd. After that, we will give an explanation of our project motivation and scope. At the end of this chapter, thesis outline will be given.

§1.1 Company Background

Headquartered in Europe, Ailter Electronic Appliances Co. Ltd is one of the leading electronic appliance companies in the world. Ailter Electronics Singapore Pte Ltd was set up in 1951. With a history of more than 50 years, Ailter Singapore is one of the pioneers in Singapore industry. Nowadays, over two hundred products are produced and sold to Asia, Europe and America. Ailter not only provides world-class electronic appliances and services to customers, but also creates over 3000 work positions in Singapore. [1]

Ailter Singapore is always trying to maintain its leading position in the electronic appliance manufacturing industry. In order to make the company more robust and competitive, production scheduling is very important in Ailter. The senior management team is eager to find more suitable production scheduling strategy for Ailter. Their continuous efforts have improved the company production performance gradually. For instance, recently, a modified Kanban policy, a world famous production scheduling policy created in Toyota Production System (TPS), was implemented in the Beta Station (Station 6 in Figure 1-3). However, many production scheduling problems still remain in this company.

§1.1.1 Factory Facilities

The facilities in Singapore are quite machine intensive due to the high labor cost. There are over 20 manufacturing stations in Ailter Singapore. Production starts from station 1 and 2 and goes through the remaining stations. These stations can be classified into two categories: process driven stations (station 1-8) and product driven stations (rest stations). The majority of products will go through stations from 1 to 8 before coming to the finished goods inventory. For the rest of stations, each one is designed to exclusively produce one product type or one type of component. Due to the complexity of the material flow, production scheduling is always an issue for the company.

Figure 1-1 is the factory layout [1]. To reduce the transportation cost, the locations of stations are designed based on production sequence. Normally the spaces between two stations are used as buffers, the sizes of which are usually big enough so that those buffers are rarely blocked.

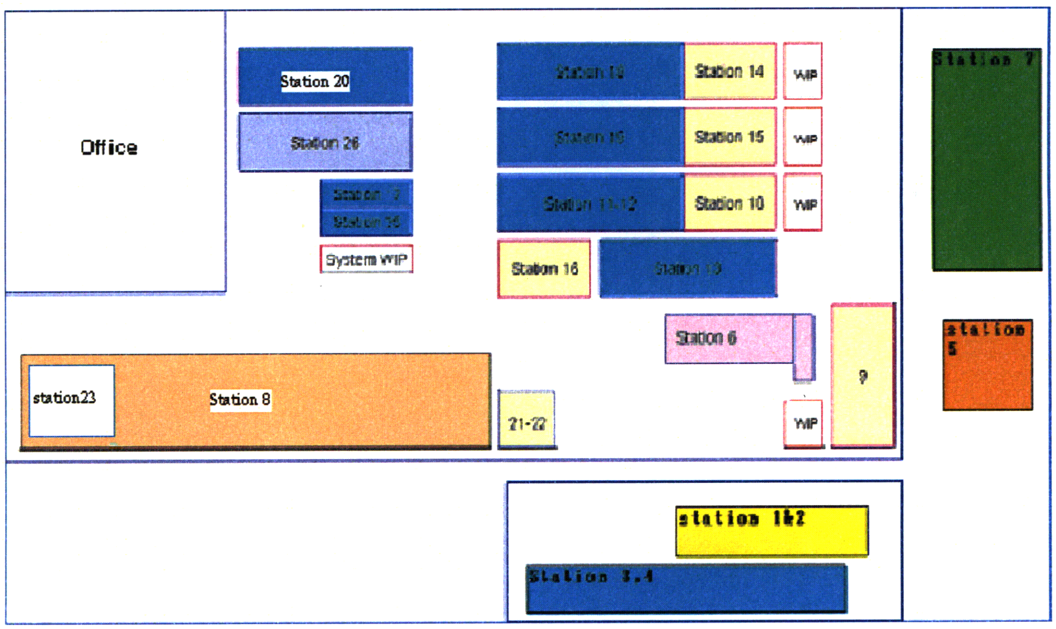


Figure 1-1 Factory layout

§1.1.2 Product Category

Based on the shape difference and different target markets, all products can be classified into three categories: A, B and C. Category A is a class of low end products. The majority of parts in this category are sold to developing countries. Category C belongs to high end products and the majority of parts in this category are sold to Europe and America. Category B counts for 65 percent of the total products and most of them are sold to Europe and America also. In each category, there are several families in order to satisfy customers' different needs. Those three product types can be divided into 9 families in total. In each family, there are different part types. You can find the distribution of product types from Figure 1-2 [1].

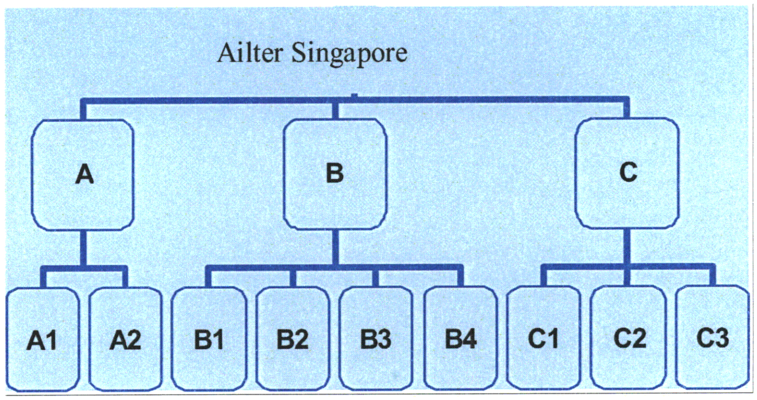


Figure 1-2 Product type

§1.1.3 Process Flow

There are more than 200 product types in this company. Generally all material flow inside the system is following the process flow in Figure 1-3. In Figure 1-3 [1], the blue rectangles stand for work stations. The red trapezoids show the buffers between two connected stations, and all the arrows are the process flow direction. All products will pass station 1 and 2. The majority of products will pass station 3. For low end products, their material flow process is usually more straightforward comparing to that of high end products.

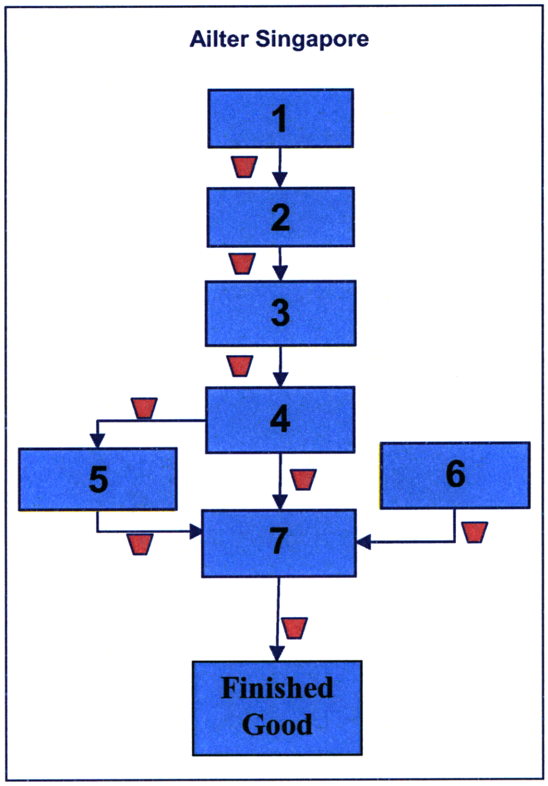


Figure 1-3 General product flow

§1.2 Motivation for this project

The company performance improvement projects were done by a team of four Master's in Engineering students from Massachusetts Institute of Technology. To achieve the goal of improving the company performance, at the beginning of the project, we spent a long period doing plant observation, interviews and analysis in order to:

- Understand the whole company performance.
- Understand the manufacturing process and material flow.
- Identify the bottleneck station and estimate problems in each manufacturing station.
- Find out the value of solving each problem and determine the area we want to focus on.

We discovered that although production scheduling is put at a very important position in Ailter, still there are lots of production problems with this factory. For example:

- There is always a tradeoff between inventory and changeover. Ailter tends to reduce their changeover times by increasing the inventory level. However, they have no idea whether this is the most profitable way.
- There are many part types. It is hard to make sure the production can satisfy all their demands while keeping their inventory to an acceptable level.
- In Ailter, they are using a fixed timeframe from January to December when doing their yearly long-term production planning. However, they did not do much research on the advantages and disadvantages of it.

§1.3 Project Scope

After system identification and comprehensive comparison, we decided to implement Control Point Policy (CPP) in this company to schedule their production. It is a real time production schedule policy developed by Dr. Gershwin from Massachusetts Institute of Technology [3]. Due to the time constraint and problem complexity constraint, instead of dealing with the whole factory, four of us decided to focus on two particular stations. At that stage, four of us were divided into two teams. Each team focused on a particular station. Xia Hua and Kai Zhao Lee implemented CPP on the Beta Station (Station 6 in Figure 1-3) while Sing Hng Ng and I implemented CPP on the Alpha Station (Station 1 in Figure 1-3). There are two versions for CPP: time-based CPP and token-based CPP. Time-based CPP was investigated in depth in this thesis while token-based CPP will be discussed in the author's team-mate (Sing Hng Ng) thesis [2] and the results for both methods as well as company current strategy will be compared before a recommendation is made to the company.

The situations for the two stations are quite different. The Beta Station is comprised of one single flow line. There is no buffer inside this flow line. Although its six-day (working 6 days per week) capacity can't meet the annual peak demand, the cumulative production capacity throughout the year is much bigger than its cumulative demand.

Meanwhile, if we consider its seven-day (working 7 days per week) capacity, throughout the year, its capacity will always be bigger than its demand. The Alpha Station is the first station in the process flow. It is the bottleneck station, the station that reduces the whole capacity of a flow line because of its limited capacity. For the Alpha Station, there are three lines in total, two auto lines and one manual line. As the improvement of this company, demand is keeping increasing from one year to another. Currently, two auto lines' total capacity can't meet the total demand for this station already. So the manual line must be used in order to make sure total production can meet total demand.

§1.4 Thesis Outline

In chapter 2, a more specific description of the Alpha Station is given. Within this context, we will discuss its current situation and the problems it is facing.

In chapter 3, a proposed solution will be described as well as a review of related literature. The whole project can be divided into two parts: optimization and simulation. Outputs of optimization are the inputs for simulation model. These two parts will be discussed in detail in chapter 4 and 5 separately.

In chapter 4, a nonlinear optimization model is built up based on minimizing total extra-cost (inventory holding cost and manual line extra-cost). Methodology for optimization is presented at the beginning of this chapter. The whole mathematical optimization model as well as the related software will be described in this chapter.

In chapter 5, simulation models of Control Point Policy (CPP) are built up. Methodology for simulation is presented at the beginning of this chapter. In this chapter, also you can find is the detailed analysis and comparison.

Chapter 6 highlights the recommendation and concludes the thesis. Future work is described in chapter 6.

Chapter 2 The Alpha Station Mapping & Problem Statement

In this chapter, we will provide a detailed introduction of the auto lines in the Alpha Station. After that, the problems attached with this station will be discussed in detail.

§2.1 The Alpha Station Mapping

The Alpha Station is the first station in factory process flow. The components produced in this station are the essential components in final products. Meanwhile, it is the bottleneck station in the whole system.

§2.1.1 Product Category

The whole station is comprised of three flow lines: two auto lines and one manual line. In total, there are five part types produced in the Alpha Lines. Part type A and B are produced exclusively in the auto line 1. Part type D and E are produced exclusively in the auto line 2. Part type C shares the biggest proportion (51.6%) among those part types. Part type C can be produced in both the auto line 1 and 2. Meanwhile, the manual line is dedicated to producing part type C. The detailed proportion of five part types produced in the Alpha Station is shown in Figure 2-2 [1]. This pie chart was calculated based on forecast demand data for year 2008.

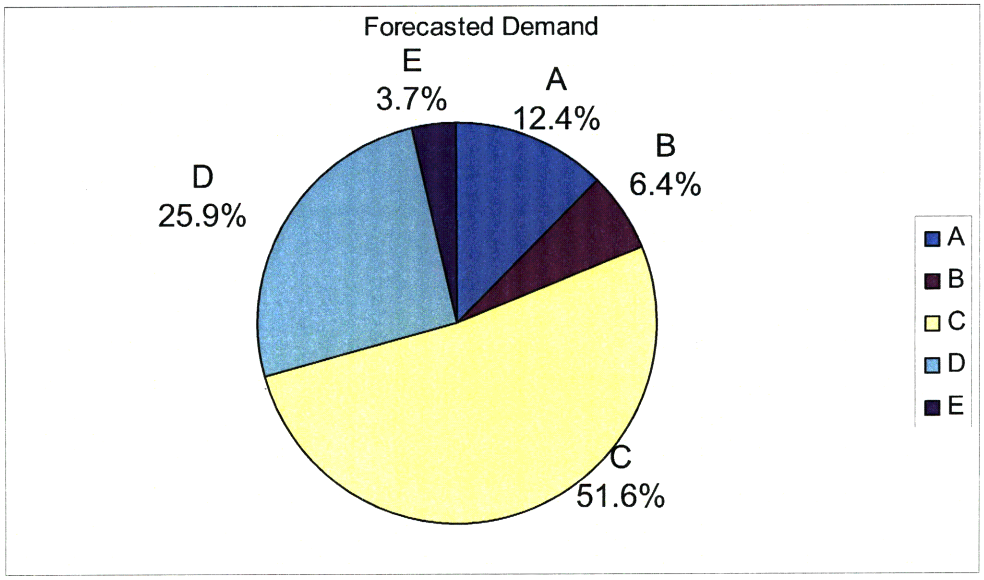


Figure 2-1 Forecast demand by part types

§2.1.2 Station Facilities

Figure 2-2 [1] shows detailed layout of the auto line 1. In total there are 7 machines in this flow line. The flow line starts from machine 1 and ends up at machine 7. Tracks or conveyors connect each two machines. Since there are two parallel tracks or conveyors operating simultaneously, two products can be produced at the same time. The auto line 2 layout is similar to the auto line 1's. Layout of the manual line is a little different because it does not have tracks and conveyors between each two machines. The biggest difference between the auto lines and the manual line exists in the operation cost. Since the auto lines are machine intensive lines, only two operators are needed for each line. While for the manual line, 7 operators are required. Since the Alpha station's installed capacity can't meet the annual peak demand in quarter 3, management has no choice but to let the Alpha Station run the manual line at times.

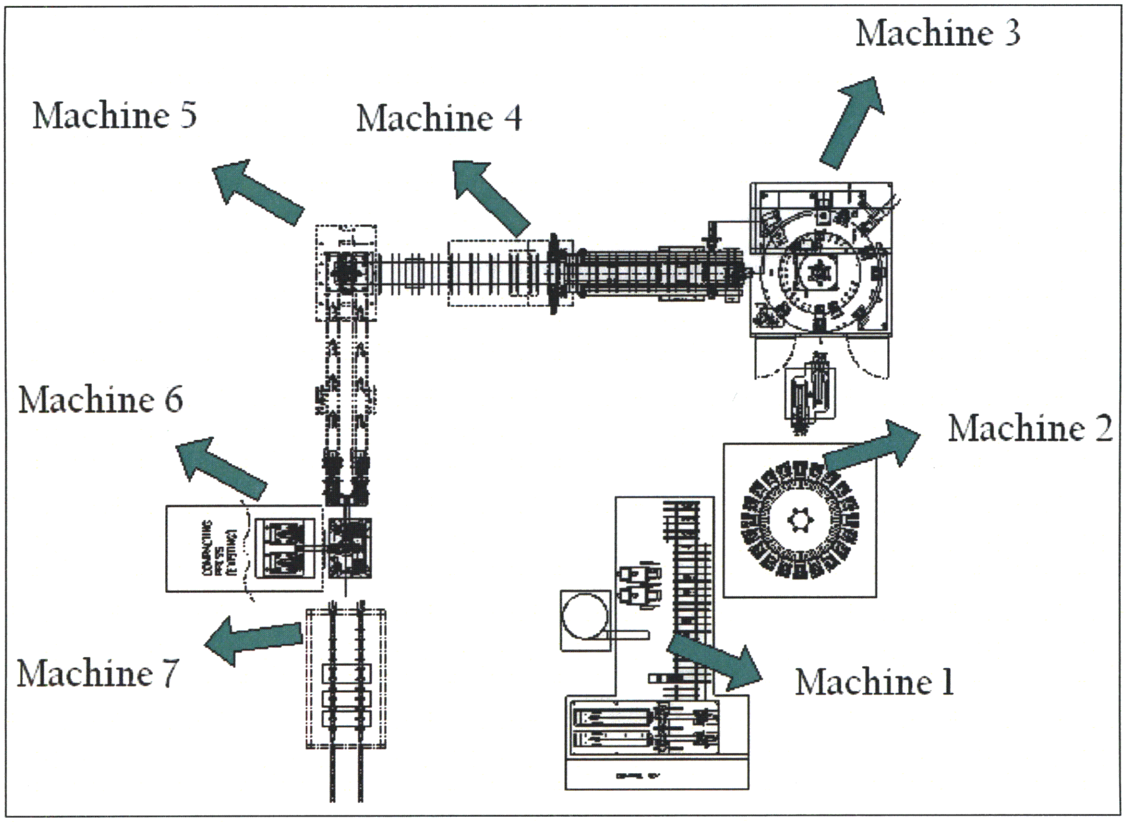


Figure 2-2 The auto line 1 layout

§2.2 Problem Statement

There are four specific problems with the Alpha station:

1. There are three lines in total. However, manufacturing supervisors do not have criteria to schedule the manual line efficiently. The manual line is used for backup. Once station manufacturing supervisors notice that they may not be able to fulfill their short term demands, they may choose to run the manual line.
2. Part type C can be produced in the two auto lines. But manufacturing supervisors do not have fixed criteria to schedule how much should be produced in the auto line 1 and how much should be produced in the auto line 2.
3. The Alpha Station may have a chance to build to stock for the next year's annual peak demand at quarter 4 of each year. However, due to the current production plan, production planners tend to keep its inventory as low as possible in the last few months of a year. That is to say, production planners give up the chance of

building stock for the next year, which may cause extra the manual line operation cost in the next year.

4. There are three part types produced at each the auto line. If exactly follow the weekly production plans given by production planers, at least there will be two changeovers per week per auto line. Since one changeover cost 1 to 4 hours, frequency of changeover will influence a line's weekly maximum production amount. Right now, station supervisors have no criterion to make a balance between frequency of changeover and the average inventory.

§2.2.1 The Current Alpha Station Stock Building Policy

The current Alpha Station stock building policy is the root of many problems described above. Figure 2-3 [1] is a comparison of yearly station capacity with its yearly demand. Green line shows the demand data. Red line is the capacity for the two auto lines. Yellow line shows the maximum production for the two auto lines if two changeovers per week are considered for each line. Blue line is the maximum production per week for Alpha Station if there are two changeovers per week for the two auto lines. One can notice that the demand is increasing from one year to the other. Nevertheless, the installed capacity for the Alpha Station has not increased since year 2005 (Capacity from year 2005 to year 2006 decrease because the company increased the production flexibility at the expense of reducing capacity). Right now, the total capacity of the two auto lines cannot meet the demand for this station. However, the total capacity of the auto lines and the manual line still can meet the total demands for the Alpha Station. As demand continues to increase, the total capacity of the auto lines and the manual line may be insufficient to meet the total demands for the Alpha Station.

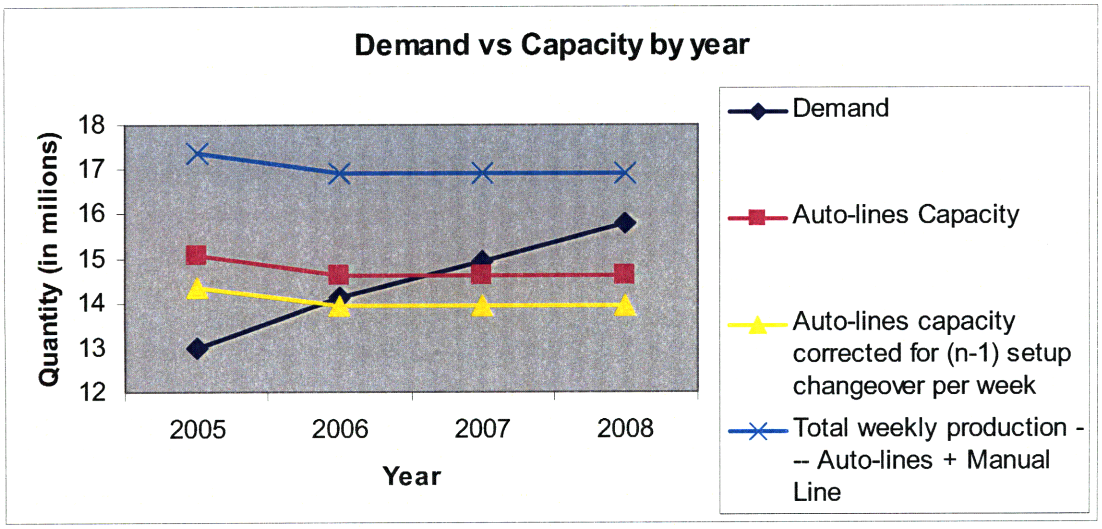


Figure 2-3 Capacity evaluation of the Alpha Station

Figure 2-4 [1] is the production plan chart for year 2007. One can notice that:

- From quarter one to quarter three, the Alpha Lines tended to operate at its full capacity. Since the total capacity of the two auto lines is smaller than 300,000 per week, which is bigger than the total capacity of the two auto lines. It means that the manual line was used some time. Meanwhile, at quarter three from week 27 to week 39 (According to Ailter calendar), the utilization of the manual line was higher than other period. (Low production rate of week 4 was due to the Chinese New Year vacation)
- At quarter four, the Alpha Station reduced their production rate in order to consume remaining stocks. That it to say, even though manufacturing supervisors noticed that they may spend more by running the manual line next year more frequently (cost of running the manual line is much higher than running the auto lines because of the high operation cost), they still prefer not to build more stock in the previous year.

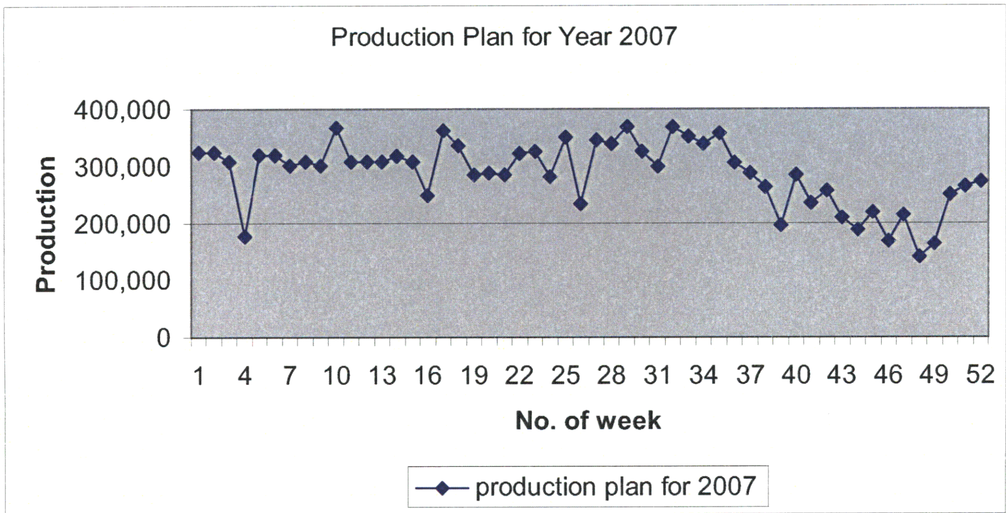


Figure 2-4 Production plan data for year 2007

As I have mentioned in chapter 1.2, commercial planners are using a fixed timeframe from January to December when doing their yearly long-term production planning. "Based on the current policy, the capacity of the last production stage is examined to determine if the demand can be satisfied. Any unmet demand is shifted backwards to the earlier months. This adjusted production demand for the last stage becomes the demand for the previous stage and the sequence follows till the first production stage." [4]

One conclusion by analyzing current stock building strategy is that the two auto lines should run at their capacity throughout the year. By doing that, the estimated production savings will be 380,395 Singapore dollars per year. The increased in inventory holding cost was estimated to be 18,718 Singapore dollars per year. So the estimated savings will be 361,677 Singapore dollars per year.

§2.2.2 The Current Alpha Station Production Scheduling Strategy

For the Alpha Station, a traditional production scheduling strategy is employed. A flow chart of this strategy can be found in Figure 2-5.

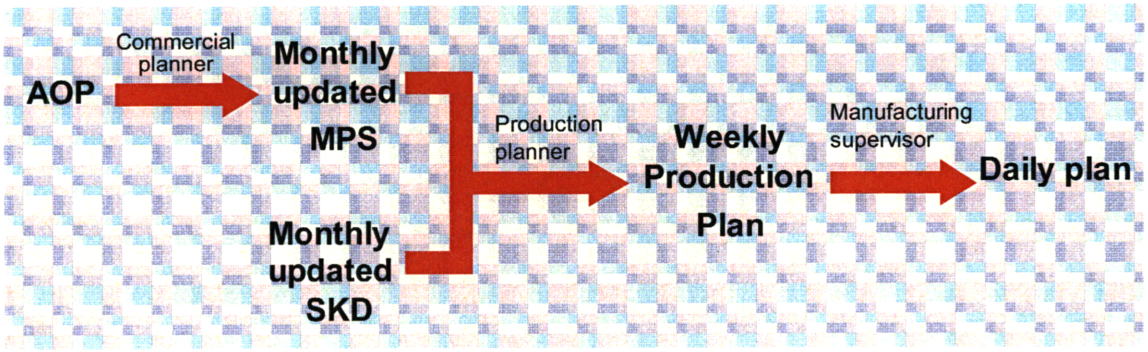


Figure 2-5 Generation process of daily plan for the Alpha Station

In September of each year, an Annual Order Planning (AOP) for the next year is made. This data specifies a base amount of products that the company should produce in the coming year to avoid financial deficit. Then, commercial planers create the Master Production Schedule (MPS) at the third week of a month for the coming month. For instance, in September 2007, an AOP for year 2008 was made. Then in the third week of December 2007, forecast data for year 2008 (January to December 2008) was made. At the third week of January 2008, the MPS for January was confirmed, and the MPS for the remaining month 2008 was updated based on some criteria. Then, those data were sent to production planners to figure out weekly production plans.

For the Alpha Station, its demands not only come from the MPS, but also from the Semi Knock Down/ annual operating plan (SKD), which is the demand from its satellite companies. Production planners will figure out weekly production plans for the Alpha Lines based on the MPS, the SKD and the system stock on hand. Manufacturing supervisors of the Alpha Station then generate daily plans based on the weekly plans given by factory production planers. Those daily plans are generated based on the manufacturing supervisors' experience purely.

Chapter 3 Proposed Solution & Literature Review

In this chapter, we will provide a proposed solution to solve the existing problems in the Alpha Station. The proposed solution will give us an abstract understanding of the methodology we employed. After that, a brief review of related literature will be given.

§3.1 Proposed Solution

To solve the problems described in Section 2.2, we brainstormed lots of solutions for each problem. After evaluation and selection, a proposed solution was set up. You can find the steps of our proposed solution from Figure 3-1.

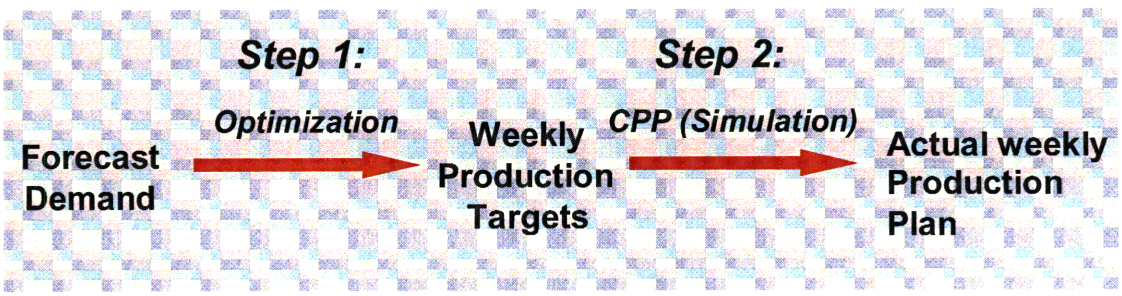


Figure 3-1 Proposed solution

The proposed solution is comprised of two parts: Optimization and the Control Point Policy (CPP). Optimization provides weekly production targets, which is the input data used by simulation of CPP to schedule auto line 1's production. (Similar CPP approach can also be employed in other stations or lines)

The objectives for optimization are:

- To provide us a stock building policy to deal with annual peak demand.
- To generate production targets for each week.
- To get the production targets for the manual line.

For more detail, please refer to chapter 4.

Based on the weekly production targets generated by optimization, CPP was employed in the auto line 1. The purpose of CPP is to provide good production performance (production rate, lead time and inventory and so on) [5]. Since the Alpha Station is the bottleneck station in this factory, we hope to increase its weekly output by reducing the frequency of changeover and to keep the inventory limited. More detail will be described in chapter 5.

§3.2 Review of Related Literature

§3.2.1 Optimization

Optimization, or mathematical programming, refers to the study of problems in which one seeks to minimize or maximize a real function by systematically choosing the values of real or integer variables from within an allowed set. The purpose of optimization is to choose the best of a set of alternatives.

To be more specific: Assume X is a set of possible choices, J is a scalar function defined on X . h and g are vector functions defined on X . Optimization is to find suitable $x \in X$ that satisfies: [6]

$J(x)$ is maximized *(or minimized)* — the *objective*

subject to

$h(x) = 0$ — *equality constraints*

$g(x) \leq 0$ — *inequality constraints*

The process to search for a suitable result can be gotten from Figure 3-2 [6]:

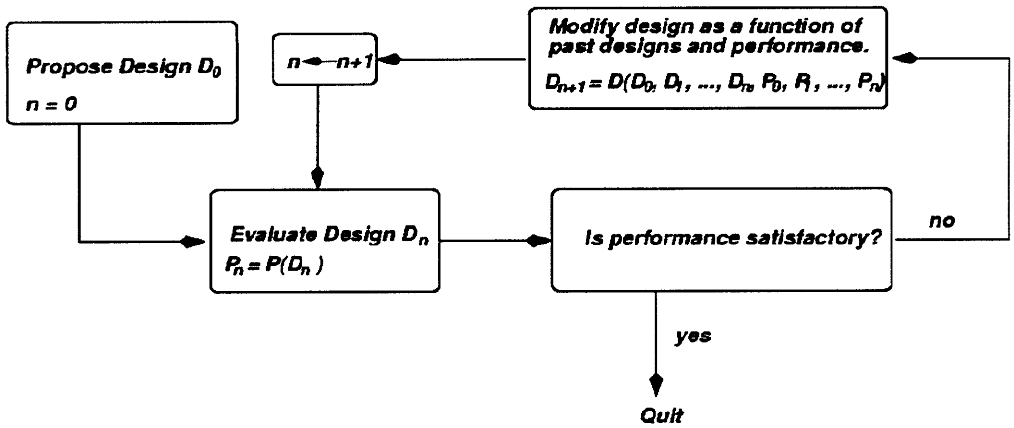


Figure 3-2 Optimization search process

Based on different criteria, optimization can be classified into:

- Dynamic/ Static
- Deterministic/ Stochastic
- X set: Continuous/ Discrete/ Mixed

Nonlinear Programming optimization problem is defined as optimization problems with continuous variables, objective, and constraints are called nonlinear programming problems, especially when at least one of J , h or g is not linear. [6]

§3.2.2 Control Point Policy

The control point policy (CPP) [3] has been developed by Dr. Stanley B. Gershwin from Massachusetts Institute of Technology. It is a real time production schedule policy. At each control point, a set of rules are provided to regulate the flow of material into or through a system by controlling how far it has overproduced. There are two versions of CPP: time-based CPP and token-based CPP. For time-based CPP, at each control point, a specific due date is assigned to each job. Time-based CPP works by controlling the earliness of a job. Token-based CPP works by controlling the inventory (Work In Progress + finished good) between a control point and the shipping dock. The token-based CPP will not be discussed in this thesis. You are recommended to refer to Mr Sing Hng Ng's thesis [2] if interested.

To get more about the policy of CPP, please refer to Appendix iv.

Chapter 4 Optimization

In this chapter, a detailed description of the methodology employed in Optimization is discussed. The process of optimization as well as the optimization model is explained. After that, the results are shown.

§4.1 Methodology

The optimization process can be divided into two steps. The first step is capacity evaluation. After getting the forecast demand data, we had a brief capacity evaluation. You can refer to section 2.2.1 for more detail. One important conclusion from capacity evaluation is that the auto line 1 must run at its full capacity throughout the year. The second step is optimization itself, which will be discussed in detail in this chapter.

§4.1.1 Model Outline

From Figure2-4 we can see that from October to December the factory has extra capacity. Meanwhile, since AOP is gotten at September of each year, we assume that forecast demand data for the next year could be available at the beginning of October. So the span of our optimization is from October to September of the next year. The fixed timeframe optimization method can guarantee that the Alpha Station will make full use of its installed capacity.

According to David Simchi Levi [7], there are three characteristics of demand forecast:

1. The forecast is always wrong
2. The longer the forecast horizon, the worse the forecast
3. Aggregate forecasts are more accurate

So demand forecast data with different resolutions is used in our optimization model. Meanwhile, since a fixed timeframe optimization strategy is used, the data in our simulation model can be divided into three parts. The first part is comprised of confirmed data (production data and demand data). The second part is the data of current month, which is separated into weeks in order to get the weekly production target data. The third part is monthly data of the remaining months. For instance, at May 2008, the data (production data and demand data) from October 2007 to April 2008 have been confirmed already. Demand data of May have been separated into weeks. While monthly forecast demand data are used for the remaining months.

The meaning of notation is shown below:

TC	=	Total Cost
IC	=	Inventory holding Cost
MC	=	Extra Cost to produce on the manual line
E	=	Extra Cost due to produce one unit on the manual line
P_{tmA1}	=	Production on auto-line 1 of part type m in time period t
P_{tmA2}	=	Production on auto-line 2 of part type m in time period t
M_t	=	Manual-line production in time period t
D_{tm}	=	Demand for part type m in time period t
CP_{tm}	=	Cumulative Production on auto-lines for part type m in time period t
IC1	=	Inventory holding cost for current month
IC2	=	Inventory holding cost for the other months
CM_t	=	Cumulative Production on the manual line in time period t
CD_{tm}	=	Cumulative Demand for part type m in time period t
I_W	=	Cost of holding unit inventory for one week
I_M	=	Cost of holding unit inventory for one month
C_{AL1}	=	Capacity of the auto line 1 per week
C_{AL2}	=	Capacity of the auto line 2 per week
C_{Mt}	=	Capacity of the manual line per time period

The optimization model can be divided into three parts:

- Variables
- Objective
- Constraints
  - Equality constraints
  - Inequality constraints

For this optimization model:

1) **Variables X:** weekly production for two auto lines and a manual line.

- P_{tmA1}, P_{tmA2} and M_t for all time period t and part type m

2) **Objective J(x):** minimize total cost TC. Total cost is considered to be total manual line cost plus total inventory holding cost. Other costs like setup cost, utility cost and common cost are not considered in the optimization model.

3) **Constraints:**

<1> Equality constraints h(x):

- Production of auto-lines equal to their capacities

$$P_{tmA1} = C_{A1t}$$

$$P_{tmA2} = C_{A2t}$$

- Quantity of inventory = $CP_{tm} + CM_t - CD_{tm}$
- IC_1 = Inventory holding cost for immediate month

= 4 or 5 weeks' inventory holding cost for 5 part types

$$= \sum_{t=1}^{4or5} \sum_{m=1}^{5} [(CP_{tm} + CM_t - CD_{tm}) * I_W] \qquad \text{(unit of t is week)}$$

- IC_2=Inventory holding cost for other months

= 11 months' inventory holding cost for 5 part types

$$= \sum_{t=2}^{12} \sum_{m=1}^{5} [(CP_{tm} + CM_t - CD_{tm}) * I_M] \qquad \text{(unit of t is month)}$$

- IC = Total inventory holding cost = $IC_1 + IC_2$
- MC = Total number of products produced on the manual line × E
- TC= IC+ MC

<2> Inequality constraints g(x):

- Production cannot be negative.

$P_{tmA1} \geq 0$ for all t, m

$P_{tmA2} \geq 0$ for all t, m

$M_m \geq 0$ for all m

- 100% service level based on optimization. Cumulative production for each part type must be bigger or equal to its cumulative demand.

  $CP_{tm} + CM_m \geq CD_{tm}$ for all t, m

- the manual line production cannot be larger than its capacity

  $M_t \leq C_{tm}$ for all t

§4.1.2 Model Assumptions

The optimization model is built based on those assumptions:

1) The auto lines are operational for 7 days/week.

2) 10% rejects are included in demand (refer to appendix iii for more detail).

3) Capacity of the manual line = 63,000/week = 252,000/month

4) Maximum weekly production for the auto line1 = 152,966/week (That number of changeovers per week is 2 is considered. This is the average weekly output data when line is running at its full capacity.)

5) Maximum weekly production for the auto line2 = 125,405/week (That number of changeovers per week is 2 is considered. This is the average weekly output data when line is running at its full capacity.)

6) Number of week in each month is gotten based on Ailter calendar.

7) Inventory holding cost is 15% considering interest rate, storage cost, handling cost and other costs.

§4.1.3 Software Used

Since the number of variables and constraints of our optimization model has exceeded the size limit of the Solver that comes with Microsoft Excel. Premium Solver Platform Stochastic Edition Version 8.0 (trial version) was used for the optimization. The Premium Solver is a basic upgrade to the Solver that comes with Microsoft Excel. It can be employed to solve linear or nonlinear optimization problems. It includes all of latest speed and accuracy improvements to the standard Excel Solver, new diagnostic reports and ease-of-use features. [8]

The size limits of Premium Solver Platform Stochastic Edition Version 8.0 are:

- Number of variables: 500
- Number of constraints: 250

§4.2 Results

Outputs of production targets from optimization are presented in Table 4-1. These data were gotten based on monthly undated demand data from October 2007 to September 2008. This table was gotten after we finished the optimization for May 2008. Since the production target data from January to May are the input data for simulation, we present them with weekly resolution.

Table 4-1 Outputs of production targets from optimization

		The auto line 1			The auto line 2			The manual
		A	B	C1	C2	D	E	
October		215054	94864	454912	91483	450358	85184	116855
November		161863	94297	355704	51901	411918	37801	246516
December		115723	90114	406027	157605	316073	27942	0
January	week1	37734	28999	86232	3059	120452	1893	59223
	week2	37481	29122	86364	3102	119054	3249	59328
	week3	36953	29386	86628	3102	118331	3972	59336
	week4	36425	29650	86892	3102	118331	3972	59344
	week5	35981	30022	86964	3102	118331	3972	59352
February	week1	19671	7335	125960	36481	0	88924	0
	week7	18968	8582	125417	109232	0	16173	0
	week8	20307	8531	124129	89296	35079	1030	0
	week9	21226	9033	122708	3819	112985	8602	0
March	week10	31552	51151	70262	31385	92856	1164	0
	week11	34678	26111	92178	15454	102628	7324	0
	week12	36068	17225	99673	13638	107106	4660	0
	week13	27639	25501	99826	6496	111585	7324	0
April	week14	77290	24530	51146	105466	9649	10290	0
	week15	35158	31294	86514	56764	62203	6438	0
	week16	35158	26026	91781	62032	56935	6438	0
	week17	29891	20759	102316	46229	72738	6438	0
	week18	34034	21294	97638	40779	84626	0	0
May	week19	31659	53782	67525	99184	0	26221	0
	week20	37584	30538	84844	34261	81464	9680	0
	week21	18209	22512	112245	18700	95297	11408	0
	week22	30862	30800	91304	0	116682	8723	40207
June		190300	132000	289564	171367	292671	37583	105569
July		278102	159500	327228	209617	359934	57474	252000
August		231298	99000	281566	167118	292315	42187	252000
September		212300	88000	311564	200343	248917	52360	163416

Because of lack of data, optimizations were done with monthly update except for May 2008, in which the optimizations were done once two weeks. The purpose of optimizations is to provide a set of production target data so that the cumulative production can satisfy the cumulative demand. And the set of production target data can make sure total cost is minimized. However, to get more accurate results, optimizations are recommended to be done once a week.

Current stock building strategy is shown in section 2.2.1. Comparing to current planning, the optimization can provide us a systematic way to build stock. Meanwhile, optimization can be used to schedule the manual line production and the manpower for the manual line. The weekly production targets for auto line 1 gotten from optimization are used as the input data for our simulation model.

Chapter 5 Time-Based Control Point Policy

In this chapter, a detailed description of the methodology employed in simulation is discussed, including the software we used and the philosophy of our simulation model. After that, the analysis of simulation model as well as the results is illustrated. The determination process of key parameters is explained in this chapter. The comparison among token-based CPP (results are gotten from my teammate Sing Hng Ng's thesis), time-based CPP and current strategy will be discussed at the end of this chapter.

§5.1 Methodology

§5.1.1 Model Simplification & Pre-simulation Activities

(1) Model Simplification

Based on the current situation of the Alpha Lines, we relax the f_s constraint. Here is the policy of time-based CPP with Setup Change after f_s constraint is relaxed [9].

Assume the machine is producing part i at time t.

1. Continue producing part i until $E_i(P_i(t)) \geq U_i$.
2. Find the set of all j (which may include i) such that:
   - $E_i < L_i$.

   If there is no such j, wait until there is. Do not continue producing i.
3. Set J to be the j with the highest priority. If there are more than one with the same highest priority, pick one.
5. Change setup to part J.
6. Set i = J and go to Step 1

You can find the block Diagram of the Control Point Policy with Setup Change in Figure 5-1 [9].

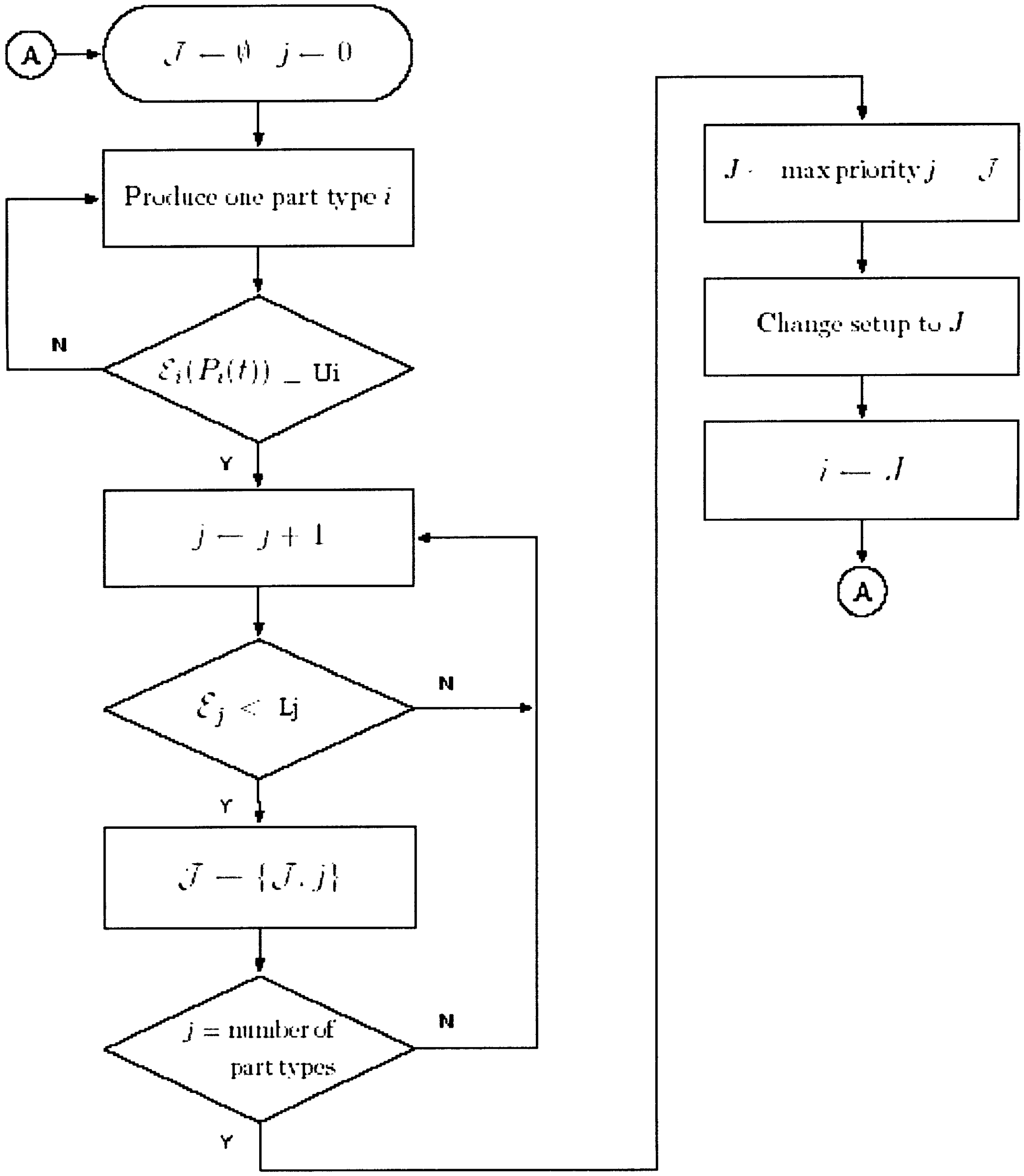


Figure 5-1 Block diagram of simplified Control Point Policy

(2) Determination of control points

Selection of control points is an important step. For the auto line 1, since the buffer sizes between each two machines are not big and the lead time for a part to go through this flow line is not long, it is not quite beneficial to set control points inside this flow line. Consequentially, only one control point was set to this flow line, which is at the beginning of this flow line. Meanwhile, the auto line 1 will be simplified to a single point in our simulation model.

(3) Model Assumptions

The simulation model is set up based on these assumptions:

- Priority A>B>C
- At time zero, all part types have met their upper hedging time
- The simulation inputs are the weekly production target data gotten from optimization from January to May, 2008 (22 weeks in total)
- The simulation inputs are discrete weekly demand input data
- The smallest time unit for hedging time is day
- Changeover time from one part type to another is 4 hours
- No supply disruption

(4) Uncertain Events

CPP can help us to deal with uncertain events. For the auto line 1, there are three types of uncertainties:

- Demand uncertainty
- Production uncertainty
- Supply disruption

The first two are far more important compared to the third one for the auto line 1. In our project, we only deal with the first two types of uncertainties. Production uncertainty will be simulated in section 5.1.3 and demand uncertainty will be considered in section 5.2.2.

§5.1.2 Software Used & Model Outline

(1) Software Used

Simul8 is professional software designed for manufacturing. Its powerful tool box provides us a quite efficient way to simulate the factory real situation. Parameters like TTR/TTF, changeover time, buffer size and service time can be easily put into simulation models as well as the distributions of some parameters. Meanwhile, the visual logic that it offers makes the software even more powerful.

The legend below is constructed to explain what the various images in Simul8 represent [2].

Table 5-1 Simul8 legend

Image	Description	Remarks
	Job release	• Use to control how jobs are released to the line
Work Center 0 	Machine	• Actual machine with inputs like TTR/ TTF, service time, etc • Allow the user to control the actual material flow through build-in functions and more importantly with codes
0 	Artificial buffer	• Not physical buffer • Use to control how the job flow through the line
0 	Work Complete	• Collect the finished goods

Note:
It is possible to change the images in Simul8 but we have stuck to the above convention for consistency.

(2) Model Outline

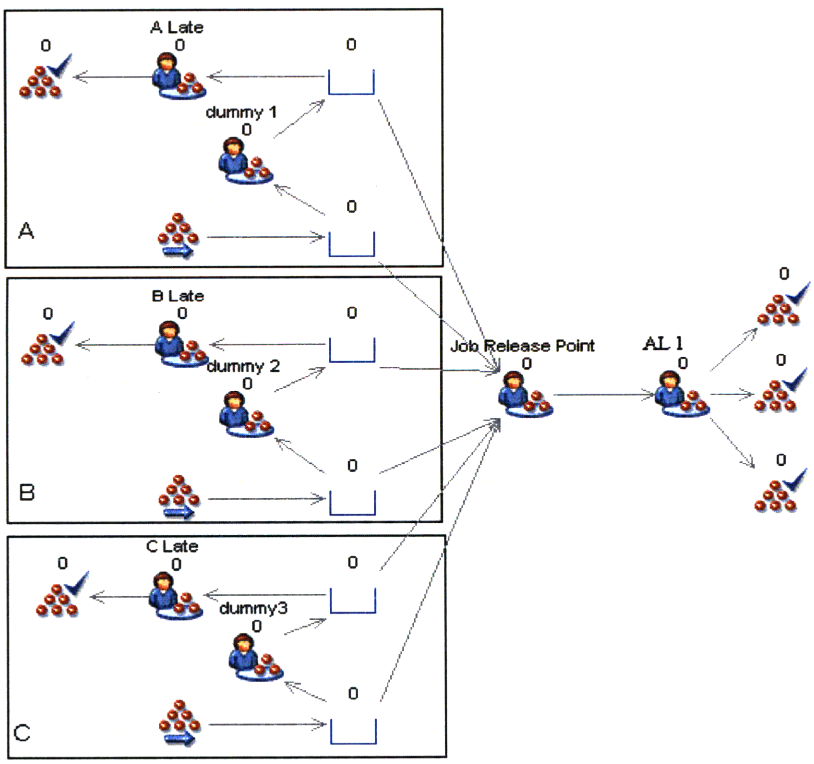


Figure 5-2 Simul8 model for time-based Control Point Policy

Figure 5-2 is the simul8 model for time-based CPP. AL1 represents the auto line 1. You can get a more clear understanding about how time-based CPP was implemented from Figure 5-3.

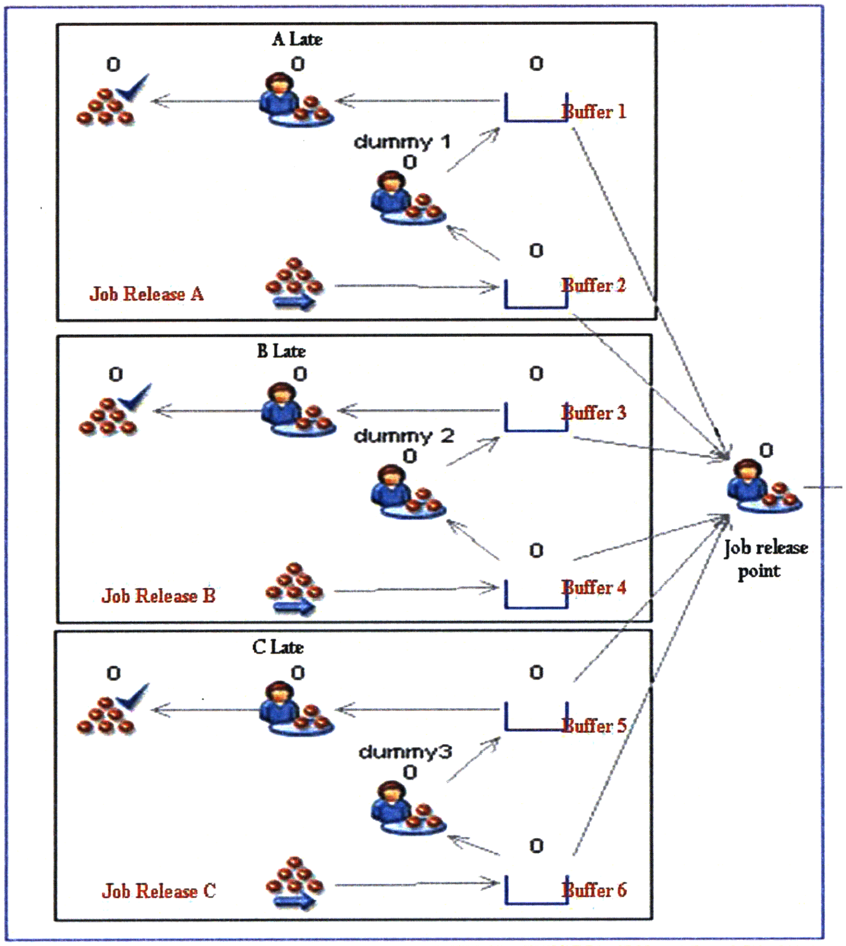


Figure 5-3 CPP logic graphical interface

From Figure 5-3, one can see that Jobs A, B and C are released to buffers 2, 4 and 6 respectively. The "earliness" in which these jobs are released corresponds to the upper hedging time as defined by CPP. When the jobs reach the lower hedging time, they are transferred from buffers 2, 4, 6 into their corresponding buffers (1, 3 and 5). The line will not manufacture if all the 6 buffers are emptied. This corresponds well with CPP which states that production be stopped if the line has reached its upper hedging time. Job

Release Point collects parts from these 6 artificial buffers by Visual logic codes. Please refer to Appendix i for sample visual logic codes used in this model.

§5.1.3 Model Validation

Mainly, there are four types of machine breakdown for auto line 1: (1) weekly preventive maintenance, (2) daily preventive maintenance, (3) Setup change and (4) random stoppage. Weekly preventive maintenance takes 8 hours (one shift). It is held once a week at a fixed time. Daily preventive maintenance will take 1 hour. It is held once a day at a fixed time except Sunday. One setup change cost 4 hours. According to current production planning, there are two changeovers per week. As to the random stoppage, by using software *Stat-fit for Simul8*, we discovered the distribution of its time to fail (TTF) and time to repair (TTR) based on the historical data. The distribution of TTR is a combined distribution by a Pearson vi distribution with parameter $\alpha 1 = 4.56$, $\alpha 2$=2.5, β=0.0408 and an offset amount offset1= 0.0287. And the distribution of TTF is a combined distribution by an Erlang distribution with parameter $k = 5$, μ=0.363 and an offset amount offset2= 0.0733 (Refer to appendix vi). Meanwhile, the auto line 1 service rate is 0.426 minute per part.

Taking into account above parameters into our initial simulation model, tests are performed (the tests are under the same condition with two changeovers per week for auto line 1). After testing, we found that the average output from our initial model (153,164 units per week) is close to auto line 1's average actual output when running at its full capacity with two setup changes (152,966 units per week).

§5.2 Analysis & Result

§5.2.1 Sample Output Data

Below are the sample outputs from our simulation model. Figure 5-4 indicates the relationship between cumulative production and cumulative demand for part type A, B and C. In this figure, areas between red line and green line are inventory (if we treat green lines as the real demands). We can calculate the average inventory based on these curves. The yellow lines are the upper hedging curves and the blue lines are the lower hedging curves. Figure 5-5 illustrates a sample output of cumulative numbers of changeovers for part type A, B and C. There is a tradeoff between frequency of changeover and the average inventory. Normally, decreasing changeover frequency means increasing average inventory. Decreasing average inventory means increasing the frequency of changeover.

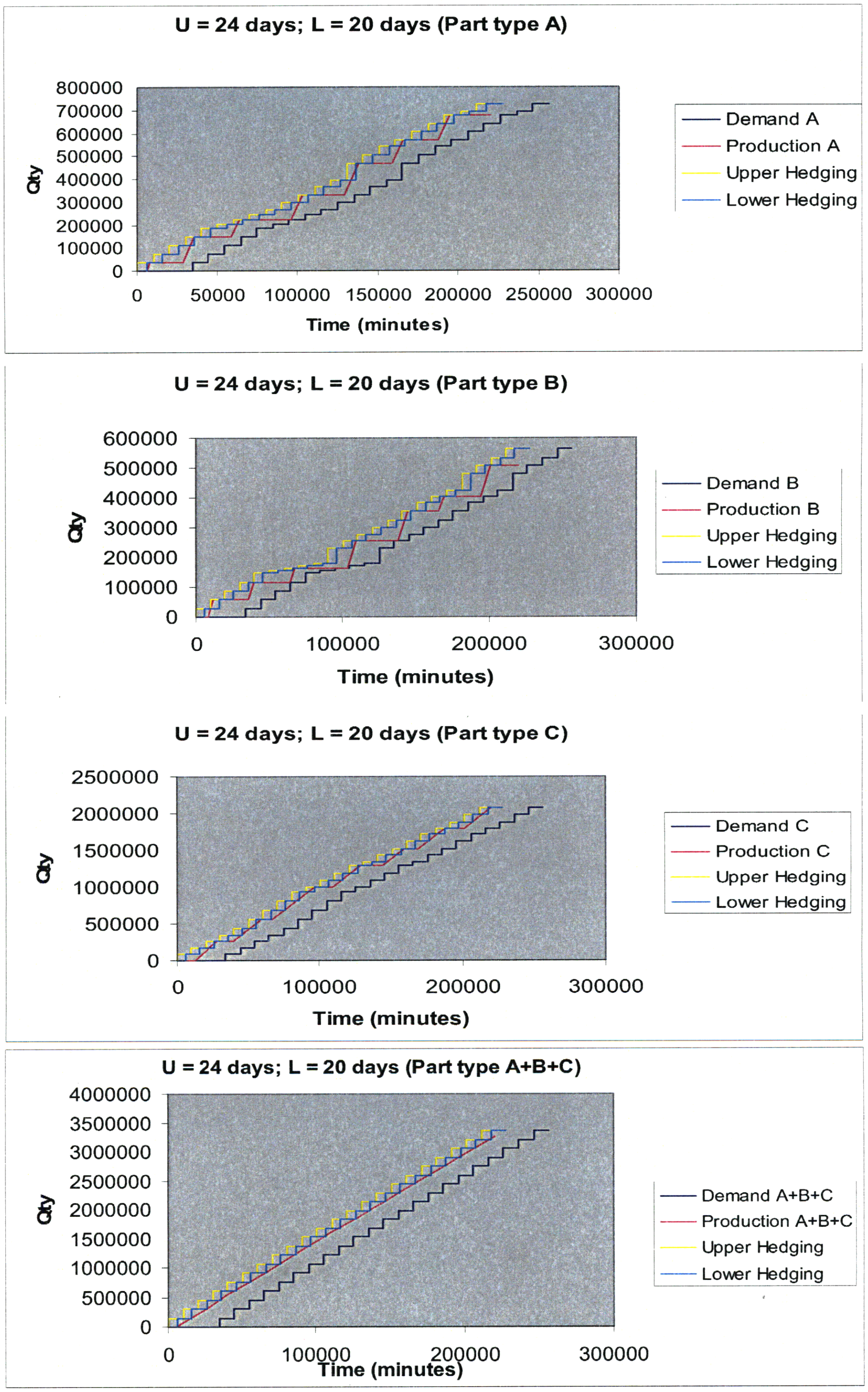


Figure 5-4 Cumulative production VS cumulative demand for part type A, B and C

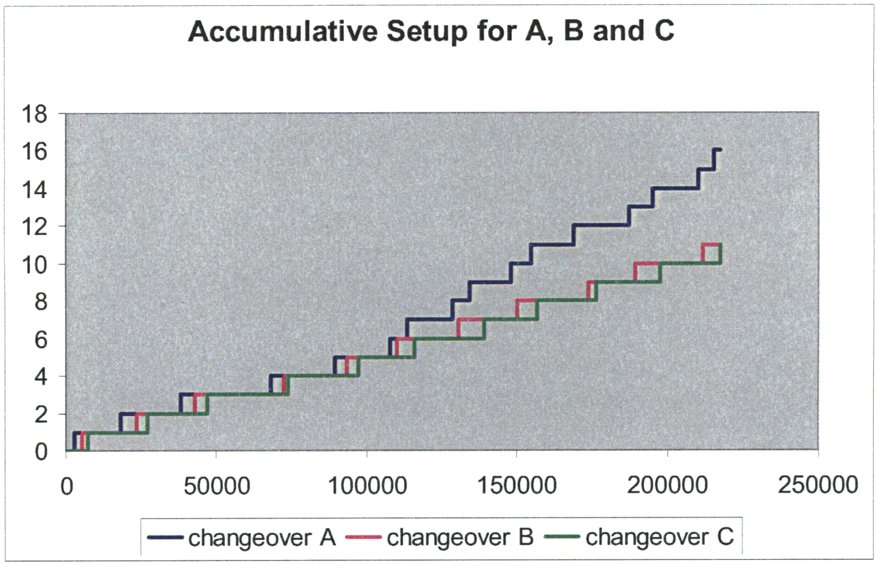


Figure 5-5 Cumulative numbers of changeovers for part type A, B and C

(Note: the chart was gotten based on scenario: U=14days, L=13days)

§5.2.1 Simulation Process & Results

Since the customer fulfillment rate is essential for Ailter Singapore, lateness is not allowed with the recommended upper hedging time and lower hedging time.

Understanding that Dr. Gershwin's time-based CPP with one hedging time is a special case of time-based CPP with two hedging time, we decided to start our researches from this special case.

By simulation, we found that hedging time (H) equals to 8 days is the best solution. If hedging time is smaller than 8 days, there will be some lateness, which is not allowed. If hedging time is bigger than 8 days, curves with the same shape will be gotten, except that the curve will move leftward (refer to Figure 5-6). Since higher hedging time will lead to higher inventory level and bigger demand uncertainty, scenario of H>8 is not as good as H=8.

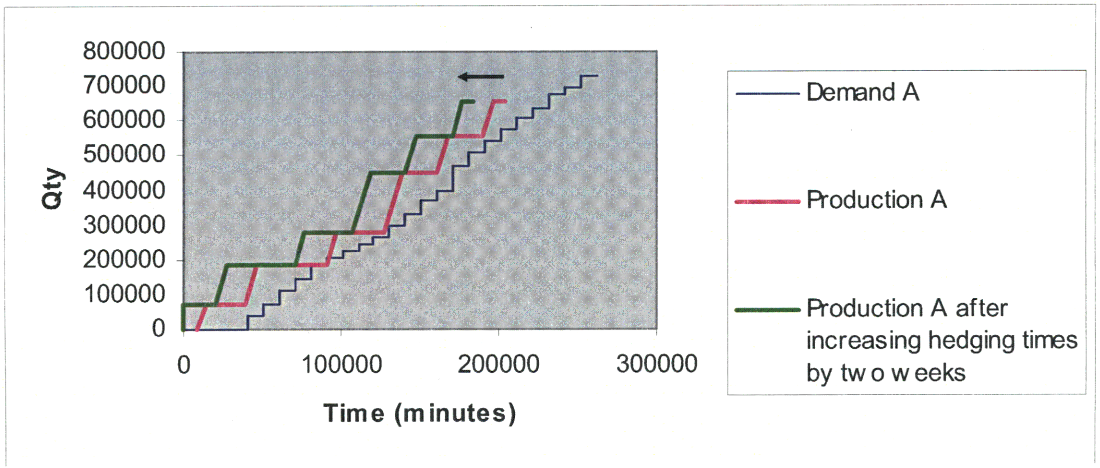


Figure 5-6 Illustrate the influence of hedging time variation

When upper hedging time (U) equals to lower hedging time (L), no matter how we varied the hedging time, total number of changeovers for the 22 weeks always stayed the same. Then we discovered that frequency of changeover is related with the difference of U and L. Understanding that for each scenario U-L=x days, there is a set of best option for U and L. we tried to find best option for each scenario from U-L=1 to U-L=7 by below methodology:

```
Initiate Set
U=7;
L=7;
Test:
If there are any lateness
        Record  Production, Lateness;
        L=L+1;
        U=U+1;
Else
        Record  U, L, Production, Inventory, Number of changeover;
        U=U+1;
```

Table 5-2 are gotten based on these tests. In this table, Average inventory data was gotten by calculating the area between red lines and green lines in Figure 5-5. Matlab (version:

R2006a) was used when calculating the Average inventory. You can refer to appendix ii for the Matlab codes.

Table 5-2 Simulation Results with no lateness

U-L (Unit: day)	Parameters (Unit: day)	Average Inventory (unit: piece)	Average changeovers per week
0	U=8,L=8	99,706	2.00
1	U=10,L=9	122,835	1.86
2	U=17,L=15	254,663	1.41
3	U=20,L=17	292,916	1.14
4	U=24, L=20	369,185	1.00
5	U=29, L=24	460,117	0.82
6	U=30, L=24	470,584	0.73
7	U=31, L=24	477,311	0.73

(Note: the data are gotten based on production target data by Optimization from January to May. There are 22 weeks in total)

§5.2.2 Consideration of Demand Uncertainty

(1) Consideration of the robustness of simulation

Purpose of simulation is to get suitable hedging time and verify the CPP's ability of providing good line performance. Since upper hedging time and lower hedging time are determined based on these 22 weeks' production target data, it is important to identify the hedging time calculated based on these inputs is also suitable for future input data. If there is some lateness, it will be treated as the safety stock to make sure no lateness will occur.

Because of lack of data, another way was employed to test upper hedging time and lower hedging time. Since auto line 1 should run at its full capacity throughout a year. We randomized the sequence of these 22 weeks' input data eight times to test the accuracy of those U and L in Table 5-2. You can find these eight sets of inputs data from Appendix v, those randomized data are gotten by using randperm() function in Matlab R2006a. After testing, the maximum lateness is gotten as you can see from Table 5-3.

Table 5-3 Maximum lateness

U-L (Unit: day)	U, L (Unit: day)	Part type	Maximum lateness	Total amount
U-L=0	8,8	A B C	0 9,033 0	9,033
U-L=1	10, 9	A B C	21,226 13,154 0	34380
U-L=2	17,15	A B C	0 0 0	0
U-L=3	20, 17	A B C	35,981 7,335 0	43316
U-L=4	24, 20	A B C	35,981 8,582 0	44563
U-L=5	29, 24	A B C	0 8,582 0	8582
U-L=6	30, 24	A B C	0 8,582 0	8582
U-L=7	31, 24	A B C	0 8,582 0	8582

Since the inventory holding cost is quite small and demand fulfillment rate are very important for Alpha Station. The lateness will be added as the safety stocks for different U and L scenarios.

(2) Consideration of forecast error

Since upper hedging time will be more then one week, weekly production plans will be sent to the Alpha Station before the corresponding week comes. For instance, if the upper hedging time is 25 days, it means the production plans should be sent to the Alpha Station 25 days before their due date (end of the corresponding week). So there will be a forecast error.

Based on the historical data, the absolute value of maximum forecast error is presented in Table 5-4.

Table 5-4 Forecast error data

Time period \ Part type	A	B	C
1 week	0	0	0
2 weeks	17600	18200	6700
3 weeks	14300	20600	7900
1 month	23600	18700	26500
1.5 month	33500	27000	92900

(Note2: because of lack of data, the safety stocks gotten above are not very accurate.)

By combining Table 5-2 and Table 5-4 together (linear interpolation is used), we can get the safety stock for each scenario as shown in Table 5-5

Table 5-5 Safety Stock

U-L (Unit: day)	**Parameters** (Unit: day)	**Safety Stock** (unit: piece)
0	U=8,L=8	15,104
1	U=10,L=9	52,594
2	U=17,L=15	42,645
3	U=20,L=17	86,154
4	U=24, L=20	98,500
5	U=29, L=24	89,413
6	U=30, L=24	101,508
7	U=31, L=24	113,603

§5.2.3 Determination of Hedging Time

(1) Tradeoff between frequency of changeover and average inventory

By adding these lateness data into the average inventory data in Table 5-2, we can get the updated average inventory data. You can find the new average inventory data in Table 5-6.

Table 5-6 Result data considering safety stock

U-L (Unit: day)	Parameters (Unit: day)	Average Inventory (unit: piece)	Average changeovers per week
0	U=8,L=8	114,810	2.00
1	U=10,L=9	175,429	1.86
2	U=17,L=15	297,308	1.41
3	U=20,L=17	379,070	1.14
4	U=24, L=20	467,685	1.00
5	U=29, L=24	549,530	0.82
6	U=30, L=24	572,092	0.73
7	U=31, L=24	590,914	0.73

(Note: the data are gotten based on production target data by Optimization from January to May. There are 22 weeks in total)

Based one Table 5-5, we can get the relationship among average inventory, number of changeovers for the 22 weeks and the difference between two hedging time as shown in Figure 5-7, Figure 5-8 and Figure 5-9. As the difference between two hedging time increases, inventory will increase and number of changeovers will decrease. There is an obvious tradeoff between average inventory and changeover frequency.

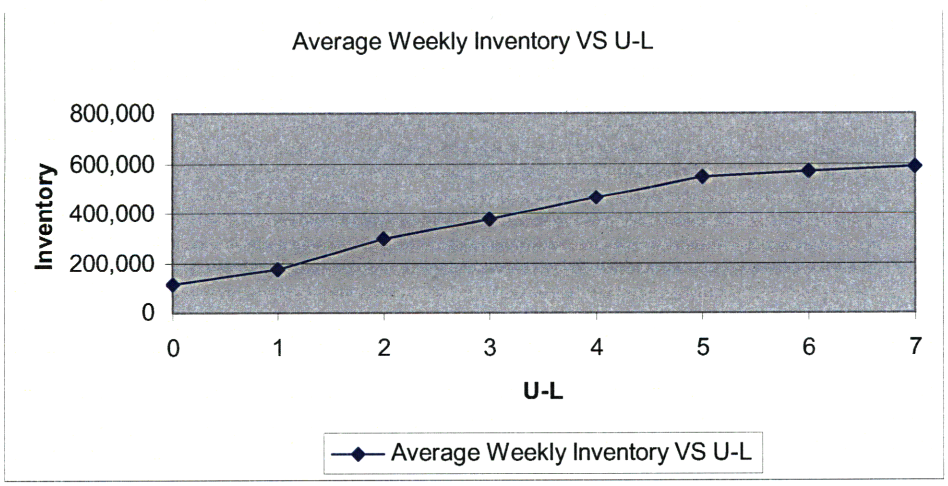


Figure 5-7 Relationship between the average inventory and U-L

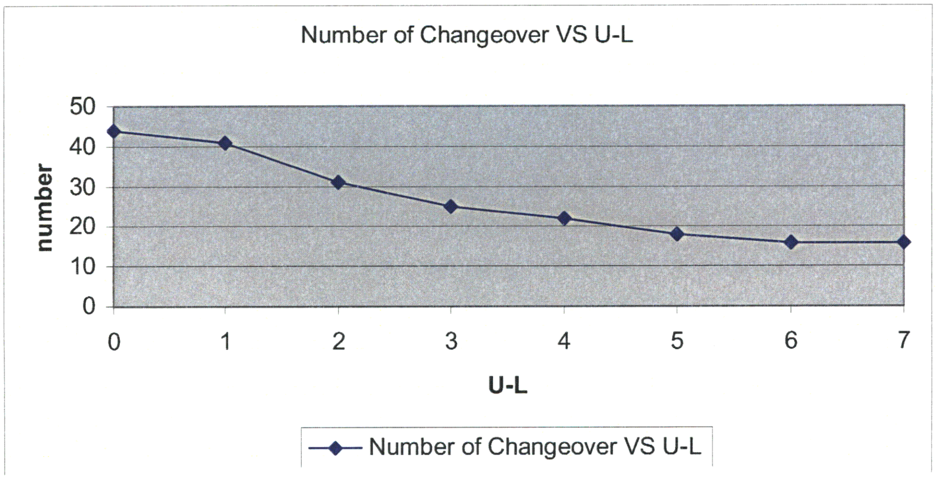


Figure 5-8 Relationship between the number of changeovers for the 22 weeks and U-L

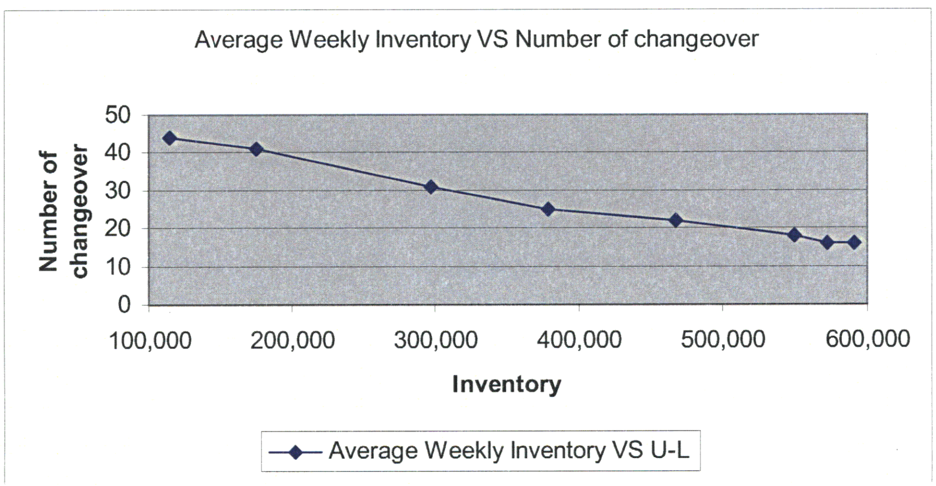


Figure 5-9 Relationship between the average inventory and number of changeovers for the 22 weeks

(2) Selection of hedging time

Based on the total cost (inventory holding cost and changeover cost), a selection will be made. According to the collected data from company, cost per changeover equals to 1012 Singapore dollars (S$253 per hour), and inventory holding cost is 15% for a year. The raw material cost per part is 0.4 Singapore dollars [1]. There are 52 weeks in a year. Based on these data, Table 5-7 can be obtained. From the chart, we can get that option U=30 and L=24 is the best option.

Table 5-7 Cost comparison

U-L (Unit: day)	Parameters (Unit: day)	Inventory holding cost per week (S$)	Changeover cost per week (S$)	Total cost per week (S$)
0	U=8,L=8	132	2,024	2,156
1	U=10,L=9	202	1,882	2,085
2	U=17,L=15	343	1,427	1,770
3	U=20,L=17	437	1,154	1,591
4	U=24, L=20	540	1,012	1,552
5	U=29, L=24	634	830	1,464
6	**U=30, L=24**	**660**	**739**	**1,399**
7	U=31, L=24	682	739	1,421

(Note S$: Singapore Dollar)

§5.3 Comparison

Table 5-8 is the simulation result of token-based CPP from Sing Hng Ng's thesis [2]. The first column stands for the difference between upper hedging level and lower hedging level. For instance, U-L equals to 5 means the difference is average daily demand times 5. Just as time-based CPP, one can notice that there is an obvious tradeoff between changeover frequency and average inventory. The highlighted row is the recommended option based on minimizing total cost (changeover cost+ inventory cost).

Table 5-8 Token-based hedging levels with no lateness

U-L (day)	Lower Hedging Level, L (in thousands)			Upper Hedging Level, U (in thousands)			Average changeover per week	Average inventory	Total cost per week(S$)
	A	B	C	A	B	C			
0	78	60	133	78	60	133	2.09	196,242	2,342
1	84	64	146	90	68	159	1.91	232,518	2,201
2	90	68	159	102	76	185	1.77	271,496	2,105
3	90	78	159	108	90	198	1.41	285,992	1,757
4	96	89	172	120	105	224	1.36	325,079	1,751
5	96	91	172	126	111	237	1.14	336,609	1,542
6	102	107	185	138	131	263	0.86	345,158	1,303
7	**129**	**103**	**212**	**171**	**131**	**303**	**0.68**	**355,918**	**1,099**
8	129	103	212	177	135	316	0.68	368,116	1,113

Currently, for the Alpha Station, a MRP is used to schedule their production. Current production planning rarely causes demand uncertainty since the Alpha Station's production is scheduled based on its weekly MRP data, which is the confirmed demand data. To avoid lateness, a large amount of finished good inventory (for the Alpha Station) is held. However, still lateness happens sometimes due to building the wrong stock.

The comparison among time-based CPP, token-based CPP and current MRP are presented in Table 5-9. Comparing CPP with current production strategy, the average inventory is a little higher. Number of changeovers is reduced dramatically from 44 to 16 or 15. Meanwhile, the odds that lateness happens will near to zero, if not equal to. Comparing time-based CPP with token-based CPP, from the total cost point of view, token-based CPP has the lower cost. Meanwhile, based on the situation of the Alpha Station, token-based CPP will be earlier to be implemented.

Table 5-9 Strategy Comparison

Strategies	Lateness	Average Inventory	Average changeovers per week	Total cost per week (S$)
Time-based CPP	Rare	572,092	0.73	1,399
Token-based CPP	Rare	328,918	0.68	1,099
Current Strategy	sometimes	~300,000	2.00	2,370

(Note: the comparison is just for auto line 1.)

Chapter 6 Recommendations, Future work and Conclusions

§6.1 Recommendations

The recommendations are summarized in the following paragraphs:

1. The auto-lines should operate at their full capacities throughout the year. Since the optimization span is from October to September of the next year, forecast demand data for the next year should be ready before October. To get more accurate results, it is recommended that optimization should be updated once a week.

2. After comparison, the token-based Control Point Policy with upper hedging levels A=144000, B=104000, C=276000; lower hedging levels A=102000, B=76000, C=185000 is finally recommended for the auto line 1. A similar strategy can be employed to determine the hedging levels for the auto line 2.

3. It is assumed that all Part types have met their upper hedging levels at time zero. Since the auto lines should operate at their full capacities throughout the year, it is necessary to utilize the manual line or to outsource the production to achieve the respective targets at the beginning.

4. From Figure 2.3, one can notice that the demand has been steadily increasing over the past several years. If the trend continues, the total capacity of Alpha Station may not be able to satisfy its increasing demand in the near future. Outsourcing may be an efficient option to deal with the increasing demand if an effective contract can be negotiated with a supplier. Meanwhile, the installed capacities for the two auto lines can be increased in certain ways to deal with the increasing demand.

§6.2 Future work

The future work is summarized in the following paragraphs:

1. During the development of the control point policy for Station A, one major challenge was to identify a good set of hedging levels. The strategy used in this thesis to determine the hedging levels is a very time consuming process as shown in section 5.2.1. A possible future research topic is to develop a strategy to search for an appropriate set of hedging levels.

2. Instead of doing the fixed timeframe optimization from October to next September, there are some other alternatives like a moving timeframe optimization with time span of 18 months and weekly update. The comparison among those methodologies can be researched in depth.

3. Right now, there are two types of preventive maintenance scheduled in Alpha Station: weekly preventive maintenance and daily preventive maintenance. The preventive maintenance costs 14 hours per week, which reduces the auto lines' maximum weekly production dramatically. A possible future research topic is to schedule preventive maintenance in a more efficient way.

§6.3 Conclusions

The strategy provided the company a systematic way to tackle the multiple part type production scheduling problems at Alpha Station. The strategy involves employing optimization and time-based Control Point Policy (CPP) in sequence. From the simulation results, one can observed that there is a distinct tradeoff between the average inventory and the frequency of changeover. After comparing the token-based CPP with the time-based CPP, the token-based CPP with upper hedging levels equal to 144000, 104000, 276000 and lower hedging levels of 102000, 76000, 185000 are finally recommended to the Ailter Singapore.

Reference

1 Company document, 2007~2008, Singapore

2 Sing Hng Ng, 2008, "Multiple-part type production scheduling for high volume manufacturing (Token-based Approach)" S.M. thesis, Massachusetts Institute of Technology, Cambridge, MA

3 Stanley, B. Gershwin, Design and Operation of Manufacturing Systems: The Control Point Policy, IIE Transactions, Volume 32, Issue 10, October 2000 , pages 891 – 906.

4 Meng Li, 2007, "An optimal stock building strategy in a manufacturing company" S.M. thesis, Massachusetts Institute of Technology, Cambridge, MA

5 Stanley, B. Gershwin, The Control Point Policy - Summary, July 11, 2007, unpublished work.

6 Stanley, B. Gershwin, Lecture notes, 2004, MIT OpenCourseWare (URL: http://ocw.mit.edu/OcwWeb/Mechanical-Engineering/2-854Fall-2004/LectureNotes/)

7 David Simchi-Levi, Philip Kaminsky, Edith Simchi-Levi, Designing and Managing the Supply Chain, 2003, New York: Irwin/McGraw Hill, page 35.

8 Premium solver help files (URL: www.solver.com)

9 Stanley, B. Gershwin and Fernando Tubilla, Proposed Setup Change Policy, March 11, 2008, unpublished work.

Appendix i -- Sample Visual Logic Codes in Time-based CPP Model

(Codes for U=29 days, L=24 days)

VL SECTION: Before Reset Logic

```
'Obeyed immediately user click RESET button (before SIMUL8 initializes simulation objects and before On Reset logic)
 SET Job Release Point.Change Over Time  =  0
 SET result_collection_row  =  1
 SET result_collection_row1  =  1
 SET temp6  =  10080
```

VL SECTION: Job Release Point Action Logic1

```
 IF Simulation Time  <=  7200
  Block Current Routing
  Break
 IF Store 1.Count Contents  =  0
  IF Store 3.Count Contents  =  0
   IF Store 5.Count Contents  =  0
    'Can block routing or continue to produce
    Block Current Routing
    Break
 IF Store 1.Count Contents  <>  0
  IF temp3  =  0
   IF temp5  =  0
    Set Route In Priority   Job Release Point ,  Store 1 ,  90
    Set Route In Priority   Job Release Point ,  Store 2 ,  80
    Set Route In Priority   Job Release Point ,  Store 3 ,  70
    Set Route In Priority   Job Release Point ,  Store 5 ,  60
    Set Route In Priority   Job Release Point ,  Store 4 ,  50
    Set Route In Priority   Job Release Point ,  Store 6 ,  40
    SET temp  =  1
 IF temp  =  1
  IF Store 2.Count Contents  <>  0
   Set Route In Priority   Job Release Point ,  Store 1 ,  90
   Set Route In Priority   Job Release Point ,  Store 2 ,  80
   Set Route In Priority   Job Release Point ,  Store 3 ,  70
   Set Route In Priority   Job Release Point ,  Store 5 ,  60
   Set Route In Priority   Job Release Point ,  Store 4 ,  50
   Set Route In Priority   Job Release Point ,  Store 6 ,  40
  ELSE
   SET temp  =  0
```

```
  Break
ELSE
 IF Store 3.Count Contents <> 0
  IF temp5 = 0
   Set Route In Priority  Job Release Point , Store 3 , 90
   Set Route In Priority  Job Release Point , Store 4 , 80
   Set Route In Priority  Job Release Point , Store 1 , 70
   Set Route In Priority  Job Release Point , Store 5 , 60
   Set Route In Priority  Job Release Point , Store 2 , 50
   Set Route In Priority  Job Release Point , Store 6 , 40
   SET temp1 = 1
   SET temp3 = 1
 IF temp1 = 1
  IF Store 3.Count Contents = 0
   IF Store 4.Count Contents <> 0
    Set Route In Priority  Job Release Point , Store 3 , 90
    Set Route In Priority  Job Release Point , Store 4 , 80
    Set Route In Priority  Job Release Point , Store 1 , 70
    Set Route In Priority  Job Release Point , Store 5 , 60
    Set Route In Priority  Job Release Point , Store 2 , 50
    Set Route In Priority  Job Release Point , Store 6 , 40
   ELSE
    SET temp1 = 0
    SET temp3 = 0
    Break
 ELSE
  IF Store 5.Count Contents <> 0
   Set Route In Priority  Job Release Point , Store 5 , 90
   Set Route In Priority  Job Release Point , Store 6 , 80
   Set Route In Priority  Job Release Point , Store 1 , 70
   Set Route In Priority  Job Release Point , Store 3 , 60
   Set Route In Priority  Job Release Point , Store 2 , 50
   Set Route In Priority  Job Release Point , Store 4 , 40
   SET temp2 = 1
   SET temp5 = 1
  IF temp2 = 1
   IF Store 5.Count Contents = 0
    IF Store 6.Count Contents <> 0
     Set Route In Priority  Job Release Point , Store 5 , 90
     Set Route In Priority  Job Release Point , Store 6 , 80
     Set Route In Priority  Job Release Point , Store 1 , 70
     Set Route In Priority  Job Release Point , Store 3 , 60
     Set Route In Priority  Job Release Point , Store 2 , 50
     Set Route In Priority  Job Release Point , Store 4 , 40
    ELSE
     SET temp2 = 0
```

SET temp5 = 0

VL SECTION: Job Release Point Before Exit Logic1

```
IF Simulation Time > 0.5
 IF temp4 <> routing_out
  SET result_collection_row = result_collection_row+1
  SET result_collection[3,result_collection_row] = Simulation Time
  SET result_collection[2,result_collection_row] = routing_out
  SET result_collection[1,result_collection_row] = temp4
  SET result_collection[5,result_collection_row] = Simulation Time
  SET result_collection[6,result_collection_row] = A complete.Count Contents
  SET result_collection[7,result_collection_row] = B complete.Count Contents
  SET result_collection[8,result_collection_row] = C complete.Count Contents
 IF Simulation Time >= temp6
  SET result_collection_row1 = result_collection_row1+1
  SET result_collection[10,result_collection_row1] = Simulation Time
  SET result_collection[11,result_collection_row1] = A complete.Count Contents
  SET result_collection[12,result_collection_row1] = B complete.Count Contents
  SET result_collection[13,result_collection_row1] = C complete.Count Contents
  SET result_collection[14,result_collection_row1] = Lateness amount A.Count Contents
  SET result_collection[15,result_collection_row1] = Lateness amount B.Count Contents
  SET result_collection[16,result_collection_row1] = Lateness amount C.Count Contents
  SET temp6 = temp6+10080
 SET temp4 = routing_out
ELSE
 SET temp4 = routing_out
```

VL SECTION: Job Release Point Work Complete Logic

SET Job Release Point.Change Over Time = 240

Appendix ii -- Matlab Code

```
function Inv = Inventory(x,y,y1)
Area =0;
Area1=0;
Inv=0;
n=size(x,1);
i=2;
for i=2:n
H =(y(i)+y(i-1))*0.5;
H1=y1(i-1);
Area=Area+H;
Area1=Area1+H1;
Inv=Area-Area1;
end
```

Appendix iii -- Calculate Reject Percentage

Utilizing the data from Week 05 – 52 of year 2007,

Total Demand = ***12,701,500 units***

Total production (corrected for rejects) = ***13,999,039 units***

Estimation of percentage rejects $\approx \dfrac{13,999,039-12,701,500}{12,701,500}\times 100\% \approx$ ***10%***

Appendix iv -- Time-based CPP Strategy

The following assumptions and notations were provided by Dr. Gershwin when he described CPP with Setup Change Policy:

- Setup time is measured in time units. The unit is arbitrary, but the units must be consistent with the units of time available for setups and setup time tokens (defined below).
- S_{ij} = setup change time from type i to type j. By convention, $S_{ii} = 0$.
- The current time is t.
- During one week, the time available for setups is
    - The total shift time – the total operation time – the total expected down time (repairs and maintenance) – a safety time.
- The allowable setup faction f_s is the time available for setups divided by the total shift time. f_s is given by

  $$fs = 1 - \left(\frac{r+p}{r}\right)\sum_i \tau_i d_i = 1 - \sum_i \left(\frac{\tau_i}{e}\right) d_i$$

  Where p = 1/MTTF is the failure rate of the machine, r = 1/MTTR is its repair rate, e = r/(r+p) is the efficiency of the machine, d_i = the demand rate for type i parts, and τ_i = the operation time for a type i part.
- There is a setup token generator putting setup tokens into a setup token buffer at the rate of fs tokens per time unit. Each token is worth one time unit of setup time. (Although we speak of tokens as though they are discrete items, the number of tokens is actually treated as a continuous quantity.)
- When a setup change from i to j occurs, S_{ij} tokens are removed from the setup token buffer.
- The setup token buffer is not allowed to go negative. This limits how frequently setups are allowed to occur.

For the time-based CPP with Setup Change, Dr Gershwin has further made the following assumptions:

- Define $P_i(t)$ to be the cumulative production of part type i at time t. Define $D_i(t)$ to be the cumulative demand of part type i at time t.
- Assume all parts have serial numbers and that they are produced and demanded in the order of their serial numbers. If the system has produced $P_i(t)$ type i parts during [0,t], the serial number of the next part to be produced is $P_i(t) + 1$. The inverse of D is the due date function; $D_i^{-1}(n)$ is the due date of the nth type i part.
- $\varepsilon_i(n)$ is the earliness of the nth part produced. If it was produced at time t, its earliness is given by $\varepsilon_i(n) = D_i^{-1}(n) - t$. Since the serial number of the type i part produced at time t is $P_i(t)$, $\varepsilon_i(n) = D_i^{-1}(n) - t$. If demand is linear, $D_i(t) = d_i t$ and $\varepsilon_i(P_i(t)) = P_i(t)/d_i - t$.
- There are two hedging times for type j: H_j^U and H_j^L. $H_j^U > H_i^L >> S_{ij}$ for all i,j. The hedging time is the time that we allow a part to remain between a control point and the end of the process)

The policy of time-based CPP with Setup Change is:

Assume the machine is producing part i at time t.

1. Continue producing part i until $E_i(P_i(t)) \geq H^U_i$.
2. Find the set of all j (which may include i) such that:
   - There are at least S_{ij} tokens in the setup buffer.
   - $E_j < H^L_j$.

   If there is no such j, wait until there is. Do not continue producing i.
4. Set J to be the j with the highest priority. If there are more than one with the same highest priority, pick one.
4. Remove S_{iJ} tokens from the setup token buffer.
5. Change setup to part J.
6. Set i = J and go to Step 1

You can find the block Diagram of Control Point Policy with Setup Change in the below Figure.

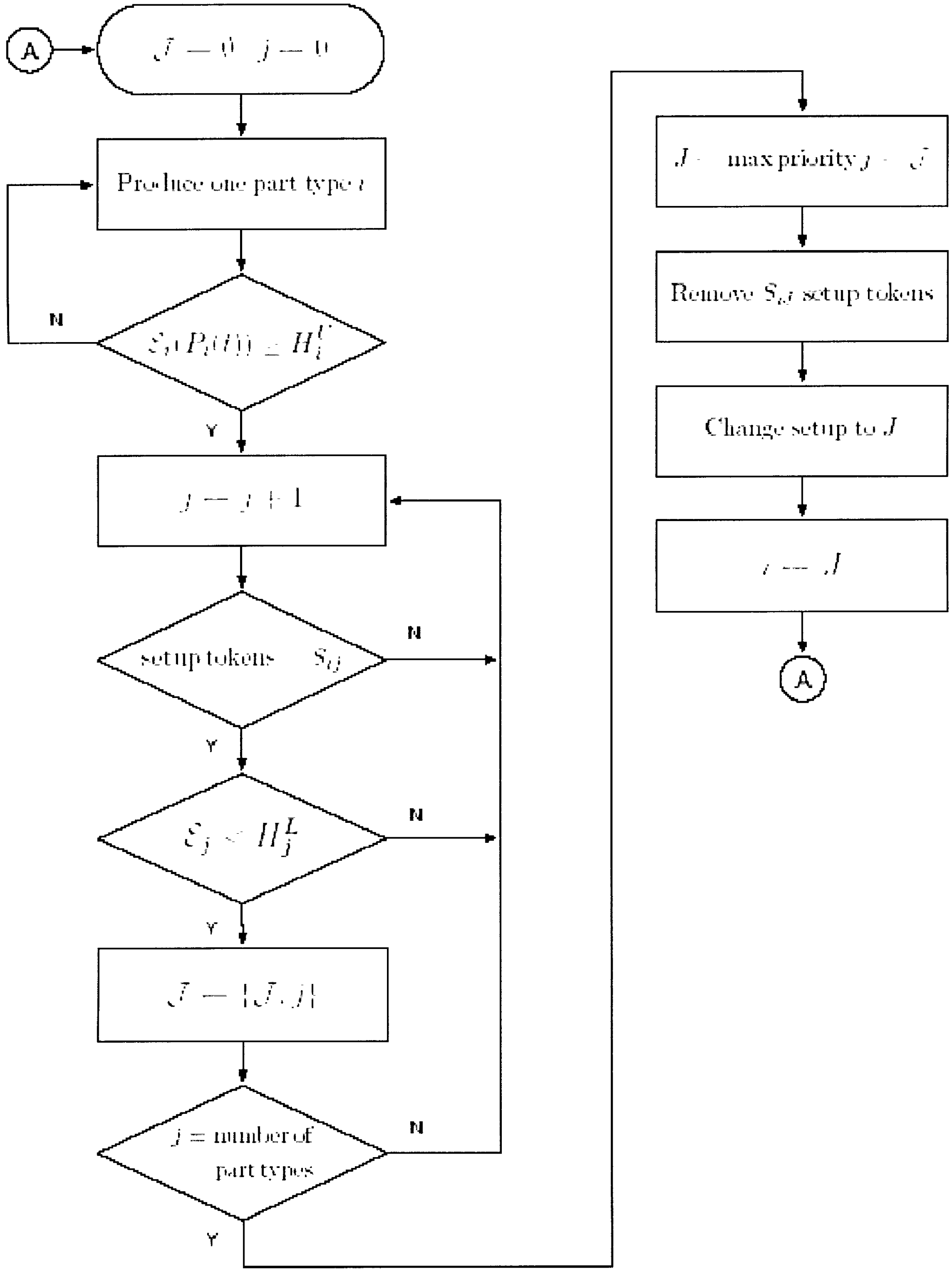


Figure: block Diagram of Control Point Policy with Setup Change

Appendix v -- Original inputs and randomized inputs for simulation

Randomized demand data:

	Original:			scenario 1:			Scenario2:			Scenario3:		
	A	B	C	A	B	C	A	B	C	A	B	C
week1	37734	28999	86232	37481	29122	86364	37734	28999	86232	31552	51151	70262
week2	37481	29122	86364	36953	29386	86628	20307	8531	124129	35981	30022	86964
week3	36953	29386	86628	36425	29650	86892	31659	53782	67525	19671	7335	125960
week4	36425	29650	86892	35981	30022	86964	37481	29122	86364	20307	8531	124129
week5	35981	30022	86964	19671	7335	125960	36425	29650	86892	36425	29650	86892
week6	19671	7335	125960	18968	8582	125417	18968	8582	125417	30862	30800	91304
week7	18968	8582	125417	20307	8531	124129	35158	26026	91781	36068	17225	99673
week8	20307	8531	124129	21226	9033	122708	36953	29386	86628	36953	29386	86628
week9	21226	9033	122708	31552	51151	70262	19671	7335	125960	35158	26026	91781
week10	31552	51151	70262	34678	26111	92178	18209	22512	112245	37734	28999	86232
week11	34678	26111	92178	36068	17225	99673	27639	25501	99826	21226	9033	122708
week12	36068	17225	99673	27639	25501	99826	31552	51151	70262	35158	31294	86514
week13	27639	25501	99826	77290	24530	51146	36068	17225	99673	31659	53782	67525
week14	77290	24530	51146	35158	31294	86514	35158	31294	86514	18209	22512	112245
week15	35158	31294	86514	35158	26026	91781	35981	30022	86964	18968	8582	125417
week16	35158	26026	91781	29891	20759	102316	29891	20759	102316	34678	26111	92178
week17	29891	20759	102316	34034	21294	97638	37584	30538	84844	37481	29122	86364
week18	34034	21294	97638	31659	53782	67525	21226	9033	122708	37584	30538	84844
week19	31659	53782	67525	37584	30538	84844	30862	30800	91304	34034	21294	97638
week20	37584	30538	84844	18209	22512	112245	34034	21294	97638	77290	24530	51146
week21	18209	22512	112245	30862	30800	91304	77290	24530	51146	27639	25501	99826
week22	30862	30800	91304	37734	28999	86232	34678	26111	92178	29891	20759	102316

Scenario4:			Scenario5:			Scenario6:			Scenario7:			Scenario8:		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
34034	21294	97638	36953	29386	86628	20307	8531	124129	37481	29122	86364	34678	26111	92178
18209	22512	112245	31552	51151	70262	18209	22512	112245	21226	9033	122708	19671	7335	125960
37584	30538	84844	37481	29122	86364	35158	31294	86514	37584	30538	84844	18968	8582	125417
37734	28999	86232	35981	30022	86964	37481	29122	86364	36953	29386	86628	21226	9033	122708
35981	30022	86964	30862	30800	91304	30862	30800	91304	35981	30022	86964	35981	30022	86964
37481	29122	86364	29891	20759	102316	35158	26026	91781	20307	8531	124129	27639	25501	99826
20307	8531	124129	20307	8531	124129	31659	53782	67525	29891	20759	102316	36425	29650	86892
34678	26111	92178	19671	7335	125960	31552	51151	70262	36425	29650	86892	29891	20759	102316
35158	26026	91781	35158	31294	86514	18968	8582	125417	18968	8582	125417	37481	29122	86364
36953	29386	86628	27639	25501	99826	36425	29650	86892	30862	30800	91304	31552	51151	70262
31552	51151	70262	35158	26026	91781	36953	29386	86628	77290	24530	51146	35158	26026	91781
18968	8582	125417	21226	9033	122708	34678	26111	92178	34678	26111	92178	37584	30538	84844
27639	25501	99826	77290	24530	51146	77290	24530	51146	27639	25501	99826	30862	30800	91304
36068	17225	99673	37584	30538	84844	19671	7335	125960	35158	26026	91781	20307	8531	124129
21226	9033	122708	34034	21294	97638	36068	17225	99673	19671	7335	125960	36068	17225	99673
36425	29650	86892	36068	17225	99673	21226	9033	122708	34034	21294	97638	36953	29386	86628
77290	24530	51146	18209	22512	112245	35981	30022	86964	18209	22512	112245	18209	22512	112245
19671	7335	125960	18968	8582	125417	37584	30538	84844	31552	51151	70262	31659	53782	67525
30862	30800	91304	37734	28999	86232	34034	21294	97638	37734	28999	86232	37734	28999	86232
29891	20759	102316	31659	53782	67525	27639	25501	99826	31659	53782	67525	35981	30022	86964
35158	31294	86514	36425	29650	86892	29891	20759	102316	35158	31294	86514	36425	29650	86892
31659	53782	67525	34678	26111	92178	37734	28999	86232	36068	17225	99673	34034	21294	97638

Appendix vi -- TTF and TTR distributions

For the random line breakdown, the historical value for the line's time to fail (TTF) and time to repair (TTR) were evaluated with the software *Stat-fit for Simul8*.

Definitions:

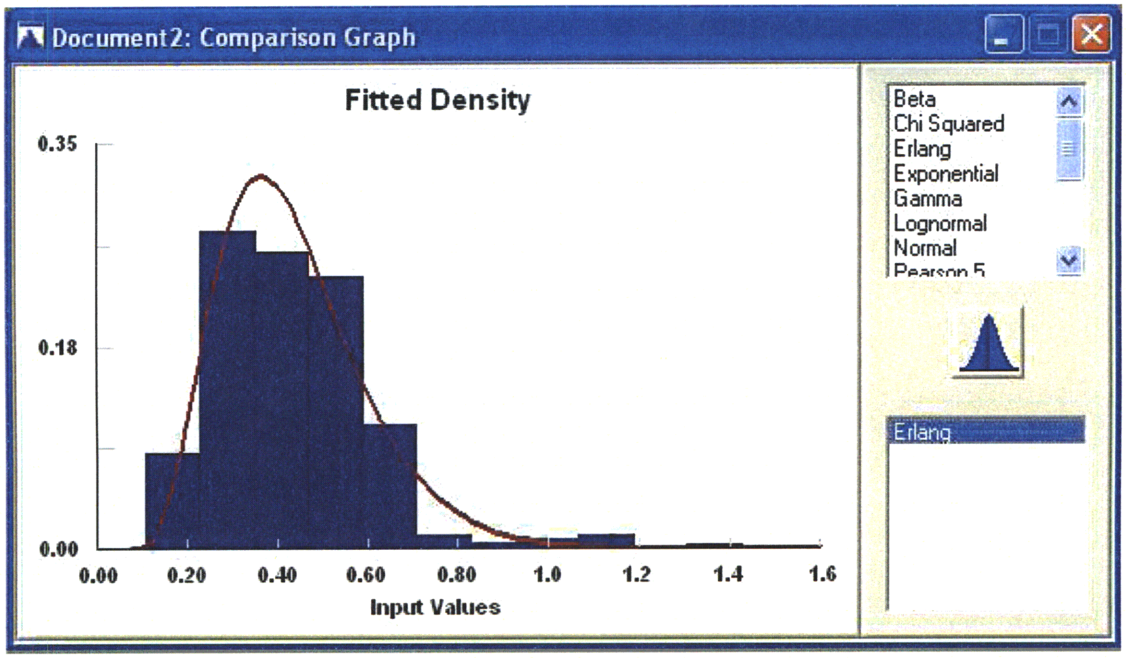
Rank: *the relative rank of a continuous distribution, given by the Auto::Fit function, which indicates the relative goodness of fit of that distribution to the input data compared to the other distributions used.* [8]

Acceptance of fit: *an indication, given by the Auto::Fit function, that the fitted distribution can be used rather than an empirical distibution.* [8]

Time to fail (TTF)

Auto::Fit of Distributions

distribution	rank	acceptance
Erlang(7.33e-002, 5., 7.26e-002)	99.8	do not reject
Gamma(7.33e-002, 4.46, 8.14e-002)	74.9	do not reject
Lognormal(-2.84e-002, -0.832, 0.363)	65.6	do not reject
Pearson 5(-0.162, 13.7, 7.57)	64.3	do not reject
Pearson 6(0.108, 2.26, 4.16, 29.5)	36.	do not reject
Beta(0.108, 1.43, 2.71, 8.1)	27.1	do not reject
Rayleigh(0.103, 0.268)	11.	do not reject
Weibull(0.103, 1.96, 0.376)	10.4	do not reject
Normal(0.436, 0.179)	3.5e-002	reject
Triangular(0.1, 1.43, 0.252)	0.	reject
Uniform(0.108, 1.43)	0.	reject
Exponential(0.108, 0.329)	0.	reject
Chi Squared(0.108, 1.01)	0.	reject
Power Function(0.107, 1.51, 0.623)	0.	reject

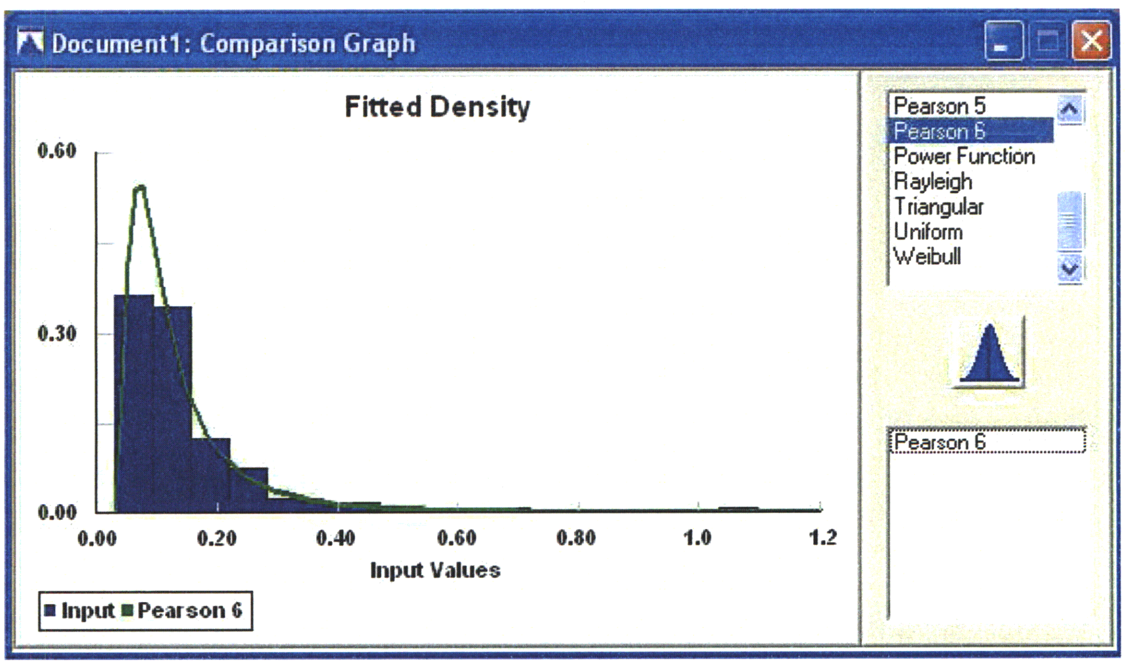


Instructions to create distribution on Simul8 model:
Create a combination distribution with a fixed offset of 7.33e-002 then add Erlang, 0.363, 5.

Time to Repair (TTR)

Auto::Fit of Distributions

distribution	rank	acceptance
Pearson 6(2.87e-002, 4.08e-002, 4.56, 2.5)	100.	do not reject
Pearson 5(1.2e-002, 2.4, 0.2)	97.5	do not reject
Lognormal(2.47e-002, -2.44, 0.824)	20.7	do not reject
Weibull(2.87e-002, 1., 0.122)	8.12e-004	reject
Exponential(2.87e-002, 0.121)	8.04e-004	reject
Erlang(2.84e-002, 1., 0.122)	5.89e-004	reject
Gamma(2.84e-002, 1.38, 8.85e-002)	5.67e-004	reject
Beta(2.87e-002, 34.8, 1.39, 394)	1.86e-005	reject
Normal(0.15, 0.141)	0.	reject
Triangular(2.53e-002, 1.1, 4.42e-002)	0.	reject
Uniform(2.87e-002, 1.09)	0.	reject
Rayleigh(-3.94e-002, 0.167)	0.	reject
Chi Squared(2.87e-002, 0.655)	0.	reject
Power Function(2.86e-002, 1.09, 0.387)	0.	reject



Instructions to create distribution on Simul8 model:
Create a combination distribution with a fixed offset of 2.87e-002 then add Pearson6, 4.56, 2.5, 4.08e-002